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Digital Terrain Modeling by Using Real Time Kinematic GPS Data

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The Postgraduate Studies Programme for acceptance, a thesis entitled

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submitted by

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for the fulfillment of the requirements for the degree of

Masters of Science in Civil Engineering

14-07-08

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UNIVERSITI TEKNOLOGI PETRONAS

Digital Terrain Modeling by Using Real Time Kinematic GPS Data

By

Dedi Atunggal SP

A THESIS

SUBMITTED TO THE POSTGRADUATE STUDIES PROGRAMME

AS A REQUIREMENT FOR THE

DEGREE OF MASTERS OF SCIENCE IN CIVIL ENGINEERING

CIVIL ENGINEERING

BANDAR SERI ISKANDAR,

PERAK

JULY, 2008

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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ACKNOWLEDGEMENT

First and foremost, I would like to thank God the almighty, for without His consent, it would be impossible to achieve what had been done in this work. And I would like to thank my parents, my wife, my son and all of my family members for their love and support from a distance to go on.

Special acknowledgement goes for my supervisor, Dr. Abdul Nasir Matori, with all of his knowledge, experience, critical thinking, and also his innumerable and invaluable contribution in this work as well as his ongoing support to complete this work.

Thanks and gratitude must be given to the members of Civil Engineering Department whom contributed their ideas, expertise and advices. Thanks to Dr. Indra Sati Hamonangan, the coordinator of Grant Assistantship in the department. Special thanks for Civil Engineering Technologists; Mr. Zaini, Mr. Meor, Mr. Ideris, Mr. Johan, Mrs. Suhaila, Mrs. Yusyawati, and Mrs. Noor for their nice cooperation during my studies.

Thanks are extended for the members of Post Graduate Studies Office for their invaluable help and cooperation.

Last but not least, thanks are given to; Mr. Bambang, Mr. Hudiyo, Mr. Basith, Mr. Suwardo, Mr Lava, Mr. Rofiq, Mr Balza, Mr. Hendrayana, Mrs. Yeni and all my colleagues and friends, who support and comfort me through the good and bad times; they have given me a lot of fun and unforgettable moments.

ABSTRACT

Total Station (TS) survey is one of the most familiar and accurate technique used for high resolution DTM data collection. However, some factors such as; intervisibility, prism targeting and unfriendly weather condition are frequently slowing down the speed of survey which mostly leads to cost inflation. Real Time Kinematic GPS (RTK GPS) offers an alternative where less surveyor needed for the survey, no intervisibility is required, and survey execution is weather independent. The materials presented in this work are based on the experiment to demonstrate the application of RTK GPS compared to TS survey. The analysis covers the accuracy, productivity, efficiency and DTM quality measure. Height and volumetric error analysis are the parameter of the DTM quality measure. Result shows that this method is capable of generating high resolution DTM up to 20cm of terrain details. RTK GPS provides sufficient accuracy as centimeter level can be achieved on terrain with average sky view above 50%. It is proven to be more productive and capable of yielding a lot more data. With the same survey duration, for an area of 62500m^2 with 75% sky view, RTK GPS could collect 568 more data and approximately 1.4 times faster than TS survey. For area with 60% sky view, the survey speed can be maintained at about 1.4 times faster than TS. For sky view 50%-60%, it shows less productivity where the survey speed of both techniques nearly the same. The application of RTK GPS on area with average sky view above 55% can produce a good DTM quality, with height errors ranging from 0.3cm-6cm, absolute mean error of 2.44cm, and the volumetric error of 0.5%. Lower quality of DTM was generated for area with average sky view between 50%-55% where the height errors and the absolute mean error are in centimeter level, while volumetric error is about 1%. Applying RTK GPS for area with average sky view less than 50% produced low quality DTM where height errors are in decimeter level and volumetric error is almost 6%.

ABSTRAK

Pengukuran Total Station (TS) merupakan teknik yang tepat dan biasa digunakan untuk pengumpulan data DTM beresolusi tinggi. Tetapi, faktor-faktor seperti jarak penglihatan antara, sasaran prisma dan keadaan cuaca yang tidak menentu sering memperlahankan kecepatan pengukuran yang boleh mengakibatkan kenaikan kos. Real Time Kinematic GPS (RTK GPS) menyediakan pilihan dimana, tidak memerlukan ramai juru ukur, tidak memerlukan jarak penglihatan antara, dan tidak bergantung kepada keadaan cuaca. Bahan-bahan kajian ini adalah berdasarkan eksperimen untuk membandingkan aplikasi RTK GPS dengan pengukuran TS. Analisis merangkumi ketepatan, produktiviti, kecekapan, dan ukuran kualiti DTM. Anggaran produktiviti dan kecekapan dibuat berdasarkan ketentuan kawasan dan masa pengukuran yang sama. Analisi kesilapan tinggi dan volumetrik merupakan parameter yg diguna untuk menentukan ukuran kualiti DTM. Hasil kajian menunjukkan bahawa kaedah ini boleh menghasilkan DTM beresolusi tinggi dengan perincian kawasan tanah sehingga 20 sentimeter. RTK GPS boleh memberi ketepatan yang cukup hingga aras sentimeter pada kawasan tanah dengan purata pemandangan langit lebih dari 50%. Kaedah ini telah dibuktikan lebih produktif dan boleh menghasilkan lebih banyak data. Untuk sebuah kawasan berukuran 62500 meter persegi dengan 75% pemandangan langit, RTK GPS boleh mengumpulkan sebanyak 568 lebih banyak, dengan anggaran 1.4 kali lebih cepat dari pengukuran TS. Untuk kawasan dengan 60% pemandangan langit, kecepatan pengukuran boleh dikekalkan pada kadar 1.4 lebih cepat berbanding TS. Untuk 50%-60% pemandangan langit, ia menunjukkan pengurangan produktiviti dan kecepatan ukuran adalah hampir sama untuk kedua-dua teknik. Aplikasi RTK GPS untuk kawasan dengan purata pandangan langit lebih dari 55% boleh menghasilkan kualiti DTM yang baik dengan kesilapan ketinggian diantara 0.3cm-6cm, kesilapan min mutlak 2.44cm, dan 0.5% kesilapan volumetrik. Untuk kawasan dengan pemandangan langit 50%-55% dihasilkan kualiti DTM lebih rendah dengan kesilapan ketinggian dan kesilapan min mutlak dalam aras sentimeter, dan kesilapan volumetrik sebanyak 1%. Penggunaan RTK GPS untuk kawasan dengan purata pemandangan langit kurang dari 50% menghasilkan DTM kualiti rendah dengan kesilapan ketinggian dalam aras desimeter dan hampir 6% kesilapan volumetrik.

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CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Digital Terrain Model

Terrain representation is essential for many engineering projects, including civil engineering and geo-information sciences. To mention only a few, terrain information is crucial in planning and construction, flood hazard assessment, geological risk mapping for reducing potential damages to oil facilities and pipelines, hydrological modeling, urban monitoring and forest fire prediction [1, 2]. In the course of these various applications, Digital Terrain Model (DTM) serve as input for decision making by integrating it to other related important data [3].

The basic concept of DTM was commenced by Miller and Laflamme of Massachusetts Institute of Technology in 1958. They developed digital profiles from set of 3D coordinates gained from stereo models of aerial photogrammetry. Nowadays, DTM refers to a representation of the so-called bare-earth surface, devoid of landscape features [4]. The definition of DTM and some similar related terms used for terrain modeling such as Digital Elevation Model (DEM) and Digital Surface Model (DSM) are reviewed in details in Chapter 2.

DTM is varied in term of spatial resolution. Low resolution DTM is suitable for small scale application (below 1:25000) which covers large areas. While, high resolution DTM is commonly used in large scale application (above 1:1000) which covers small area. The later is recurrently requisite in civil engineering where many of its large scale projects required high details and accurate terrain information [5].

1.1.2 DTM data collection techniques

DTM has been a very useful mean for representing terrain surface. Terrain information is currently obtainable from aerial photogrammetry, optical and radiometer images, interferometric and synthetic aperture radar; light detecting and ranging technique, and land surveying.

DTM is an integral part of every aerial photogrammetry workflows. This technique is still in use in many applications particularly for DTM generation and topographical mapping of medium to large areas [6]. Nevertheless, the expenditure of DTM data acquisition using this technique is deemed to be costly and time consuming, especially when used for large scale engineering application.

Remote sensing by radiometer and optical satellite images offer raster DEM in varied spatial resolutions. The processing of data acquired in the C band by the Shuttle Radar Topographical Mission (SRTM) provides a nominal 30m DEM of over 80% of the earth landmass surface with an approximated vertical accuracy of 15m [7]. This spatial resolution is reduced to 90m pixels for area outside USA [8]. With this spatial resolution, these data is commonly employed for the generation of medium to low resolution DTM.

Stereo optical satellite images acquired by IKONOS™ and QuickBird™ furnish another means to acquire DTM. The spatial resolution of these satellite images is 1m and 0.6m respectively. Consequently, the accuracy of DTM derived from these is lower than the respective mentioned spatial resolutions. Furthermore, the successful processing of these images highly depends on the sun illumination and cloud covering conditions [9]

Light Detection Ranging (LIDAR) or known as laser scanning, offers another means to acquire DTM, particularly for high resolution DTM. The Airborne Laser Scanning (ALS), one of the members of the LIDAR technology has been tested and proven to have a few decimeter accuracy [10]. Nevertheless, the distinction between surface and terrain is often difficult [11]. Besides, at present time, laser scanning is still relatively costly in terms of equipment instrumentation, survey execution and data processing cost.

Compared to previous mentioned techniques, traditional land surveying using theodolites or computerized Total Stations (TS) still provides the highest accuracy, up to sub centimeter level [6]. Therefore, high fidelity to the original surface can be preserved by the digital data. Land surveying using total station has been the main tool for civil engineers and surveyors for DTM data acquisition as well for stake out survey and large scale mapping.

All the above data collection techniques can be used to acquire DTM. It should be highlighted that each have advantages and disadvantages. Photogrammetry and remote sensing are commonly applied on the generation of medium to low-resolution DTM covering large area. Meanwhile, laser scanning and land surveying are usually employed for high-resolution DTM generation. Certain filtering processes are required for DTM generation by photogrammetry, remote sensing, and laser scanning since the direct derivative of those data is DEM or DSM representing the earth with all its landscape features and land coverage.

1.1.3 GPS in DTM data collection

Global Positioning System (GPS) plays an important role in DTM data collection. GPS particularly static positioning (including; stop and go, fast static and rapid static) has been used commonly for establishing tie points used on DTM generation from stereo aerial photos and satellite images [12]. These GPS technique have been also employed for generating DTM and determining local geoid solution (reference height approximated by Mean Sea Level or MSL) [13].

Kinematic GPS technique has been employed for DTM data acquisition and capable of giving centimeter level of accuracy [7]. Real Time Kinematic (RTK) GPS is frequently used as a verification reference for DTM which is derived from photogrammetry, remote sensing, and interferometric as well as synthetic aperture radar [10].

GPS technology, in particular Real Time Kinematics GPS (RTK GPS), has been leveraged to the point in which it has become another effective spatial data collection tool for professional surveyors. Commercial products provide user-friendly hardware/software and recommend techniques that can improve productivity at a high accuracy [14].

1.2 Problem Statement

The use of DTM within the entire civil engineering community has to be assessed from technical and financial point of view. These reasons specifically deal with the data capture phase of the DTM, where the greatest time and cost are recognized. Criteria that must be considered when evaluating acquisitions methods and systems are; accuracy, productivity, cost effective, repeatability, and ease of use.

Land surveying using TS is the most familiar and accurate technique that has been used in civil engineering projects. Yet, some factors such as; intervisibility requirement, prism pole targeting and unfriendly weather condition during the survey execution is frequently slowing down the speed of survey which mostly leads to cost inflation. Moreover, in term of efficiency, land surveying using Total Station is more labor intensive which consequently requires more personnel expenditure.

Technically and theoretically, RTK GPS offers alternative solution but in practice, many practitioners are still reluctant to adopt the application of RTK GPS for DTM data collection in particular and large scale mapping in general. This is due to a number of reasons such as a lapsed understanding on the technology, confusion about GPS surveying capabilities and best practice techniques, uncertainty over how to best utilize existing GPS service and infrastructure, and lack of time/resources to invest in the technology [14].

1.3 Objective of Study

The key purpose of this research is to experimentally study the application of Real Time Kinematic GPS as data acquisition tool in the generation of high resolution DTM. The main objectives of the research are:

i. To establish a high resolution DTM by taking a portion of the campus area of Universiti Teknologi PETRONAS as a study area.
ii. To assess the accuracy of RTK GPS as DTM data collection tool, and to characterize the quality of the generated DTM, by validating it against the conventional technique of land surveying by using Total Station.
iii. To asses the productivity and efficiency of the proposed technique.

1.4 Scope of Study

The scope of this work is to study the application of Real Time Kinematic GPS for DTM data collection. However, to have a comprehensive analysis, the whole process of digital terrain modeling is carried out. It encompasses the process of DTM data collection, data processing and representation, and also DTM quality measures.

DTM data collection is conducted by using two types of data sampling techniques. Composite sampling is performed to adapt the application of RTK GPS in the nature of land surveying in which TS is commonly employed. Grid-based sampling is carried out to provide the basis of the DTM quality measure. TS survey is used as the reference for the productivity and efficiency estimation as well as for the DTM quality measures. This is due to the fact that TS is the conventional technique that can provide high accuracy of millimeter level but slow in term of survey speed. The representation of the DTM is generated using TIN-based (Triangular Irregular Network) approach.

DTM quality measures are carried out by taking height error analysis together with volumetric error analysis. DTM generated from TS data is used as the reference DTM.

1.5 Organization of Thesis

The overview of digital terrain model has been given at the background section of this chapter, continued by problem statement, objective, scope of study and organization of the thesis.

Chapter 2 outlines the literature review on digital terrain modeling concepts and theories, as well as best practices and guidelines. Other important sources such as text books and standards are also consulted.

Chapter 3 explains the experiment procedures and processes done on the research. Essential fundamental concept and theories pertaining to the research methodology are also highlighted.

Chapter 4 focuses on the results and discussions of the work done.

Chapter 5 gives an overall summary of the research, followed by the conclusion of the work done and recommendations for future work.

CHAPTER 2

DIGITAL TERRAIN MODELING

2.0 Introduction

This chapter is outlining a review to relevant literatures on digital terrain modeling, much of which has been published internationally. Special note has been made of those papers discussing the concepts and best practices of digital terrain data collection, processing, representation and quality measure as well as related cases and issues pertaining to them. Other important sources such as textbooks and standards are also consulted and assessed.

Digital terrain modeling has been in existence for years. Its applications have been constantly evolving, developing and adapting to the changing needs of a multi-discipline workplace. As the use of this grew, it is now widely used in many scientific, commercial and industrial applications, such as [2];

i. Scientific applications:
   Hydrological modeling, landscape analysis, climate impact studies, water and wildlife management, geology, mapping and surveying.
ii. Commercial and industrial applications:
   Planning and construction, telecommunication, geological exploration, air traffic navigation, meteorological services, oil facilities and pipelines monitoring

In addition to the applications above, digital modeling of terrain surface allows the computation of many derived products. Slope, aspect, curvature, visible area from a point or cut and fill volumes are only a few examples of the large number of derivatives which can be generated from a digital terrain model.

Digital terrain model is varied in term of spatial resolution. Large scale application covering small area requires high resolution data while low resolution data is sufficient for small scale application (large area). Many civil engineering projects are in large scale application, therefore, high resolution digital terrain model is major importance. As an example, high resolution digital terrain model is very essential for civil engineering projects such as; planning and construction, road design, sewer and drainage monitoring, flood risk assessment, landscape planning, etc.

The term of high resolution is commonly correlated with the scale of the application. Applications on scale 1:1000 or above are usually referred as large scale application which requires high details of terrain information. Height or contour intervals that commonly applied for this particular application are usually at 20cm, 30 cm or 60cm [15]. While, application on scale 1:25000 or below is considered as small scale application where low resolution DTM will suffice.

There are several criteria that have to be fulfilled for full scale of acceptance on the application of digital terrain modeling within civil engineering projects. This is specifically dealt with the data capture phase where the greatest cost and time is recognized. The criteria regarding to the data acquisition phase are as follow [1, 3, 6, 15]:

i. Accuracy appropriateness
ii. Timely deliverables
iii. Cost effective
iv. Repeatability
v. Ease of use

Therefore, all the above criteria have to be considered in assessing and choosing suitable DTM data collection method, especially for civil engineering projects. Data processing and representation are an integral part of the work, as well as quality measure of the generated DTM. Reviews on related concepts, theories, standards, best practises and previous findings from other studies are the main focus for this chapter.

2.1 Digital Terrain Model

Terrain model has been developed for years. Formerly, it was presented in a physical model, made of clay, rubber, plastic etc. Mathematical and digital techniques for terrain modeling were initiated by Miller and Laflamme of Massachusetts Institute of Technology in 1958. They developed digital profiles from set of 3D coordinates gained from stereo models of aerial photogrammetry. They also introduced the basic concept of the digital terrain model. The definition given by them are as follows [16]:

> The digital terrain model (DTM) is simply a statistical representation of the continuous surface of the ground by a large number of selected points with known X, Y, Z coordinates in arbitrary coordinate field.

Currently, digital terrain model refers to the representation of the so-called bare-earth surface, devoid of landscape features [7]. Beside DTM, there are some other terms used in terrain surface modeling such as digital elevation model (DEM), digital surface model (DSM), digital ground model (DGM), digital height model (DHM) and digital terrain elevation model (DTEM).

Practically all the above terms are often considered to be similar but in fact some of them refer to different products. DGM and DHM terms are used locally in United Kingdom and Germany respectively, while DTEM is used by the United States Geological Survey (USGS) [6]. The term DEM has been differently defined by various authors [17]. Burrough [18] defined DEM as any digital representation of continuous variation of relief over space. DEM is also defined as an ordered array of numbers that represents the spatial distribution of elevations above some arbitrary datums in the landscape [19]. Initially, DEM is used by USGS to describe a set of elevation values representing the elevations at points in a rectangular grid on the earth's surface [20]. This term has been widely used in the area of earth surface modeling. In parallel with the advancement of terrain modeling study, the definition of DEM is developed and become more general. At present time, it includes both gridded and non-gridded datasets [1].

The different between DEM and DTM as stated by many author is that DTM is a filtered version of what was originally DEM. Lemmen [21] stated that DTM is DEM extended with structural features such as drainage channels, ridges, hilltops, depression and other terrain discontinuities. Meanwhile, Wilson and Gallant [22] described that DTM is DEM complemented with breaklines, where breaklines are lines in the topography where grade changes exist, such as tops and toes of slopes. Underwood [23] depicts breaklines as the line along abrupt changes in slope. Figure 2.1 gives the illustration of breaklines.

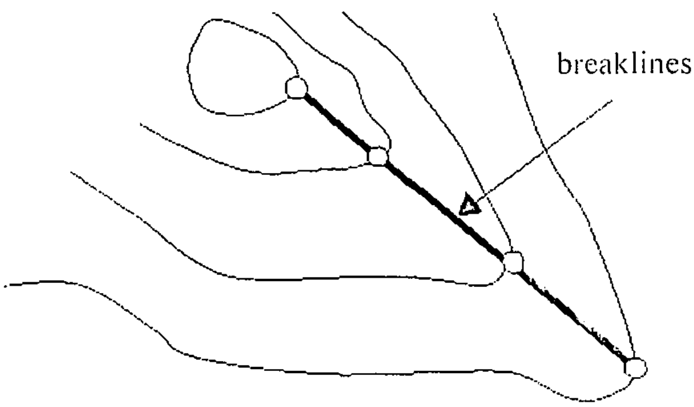


Figure 2.1 Illustration of breaklines [23].

The term DSM generally refers to a representation of the earth's surface, including landscape features such as vegetation and buildings [7]. Nearly similar to the previous definition, Dowman et al [24] stated that the term Digital Surface Model (DSM) refers to a DEM, which represents the elevation of the first surface of a remote sensing system. Therefore, the resulting DSM includes the elevations of both, man-made such as buildings and natural surface features such as trees, shrubs and crops, elevated above bare earth [24].

The different between DSM and DTM is illustrated in Figure 2.2. DTM represent the elevation information of the bare earth and the water surface. Thus, a DTM is a representation of the true terrain of the Earth's surface. From this point of view, DTM can be extracted from a DSM or DEM by applying certain filter. Hence, the quality of a

DTM which is derived from DSM or DEM is highly depended upon the algorithms used to eliminate surface features that cover the bare earth, among various other factors.

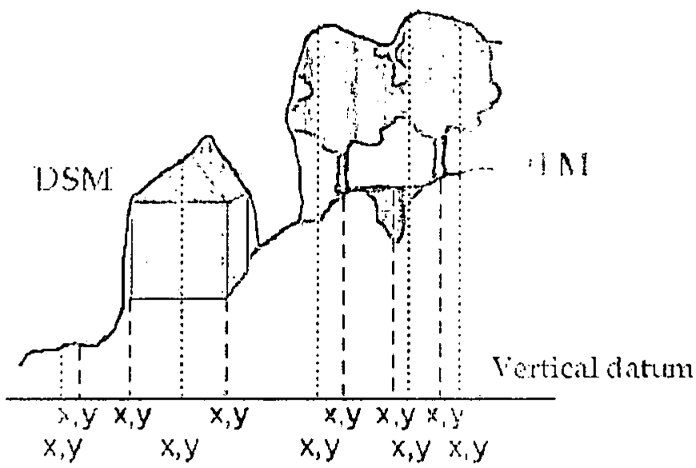


Figure 2.2 Graphical illustrations of DTM and DSM [24].

2.2 Digital Terrain Modeling

Digital terrain modeling is the process of generating DTM [6]. Generally, it is carried out in several stages that is; data collection, processing, representation and validation or quality measure [6]. Data acquisition is the process of data collection of continuous terrain surface by using a particular technique. It covers the process of points sampling from the terrain with certain observation density and distribution. Data processing is the process of terrain reconstruction based on the collected sampling point. Interpolation is required to complement attributes on the location of the digital surface which is not covered by the sample points. Quality measure is the process of DTM error characterization. This is commonly declare by a number of variable such as; roughness, density, distribution, volume loss and accuracy.

In practice, from a project-based point of view, digital terrain modeling is a complex process. It also comprises several processes such as; contracting, feasibility assessment, planning and design, terrain classification, data verification, and quality control and shipment [6, 25]. The detail process of digital terrain modeling is illustrated in Figure 2.3.

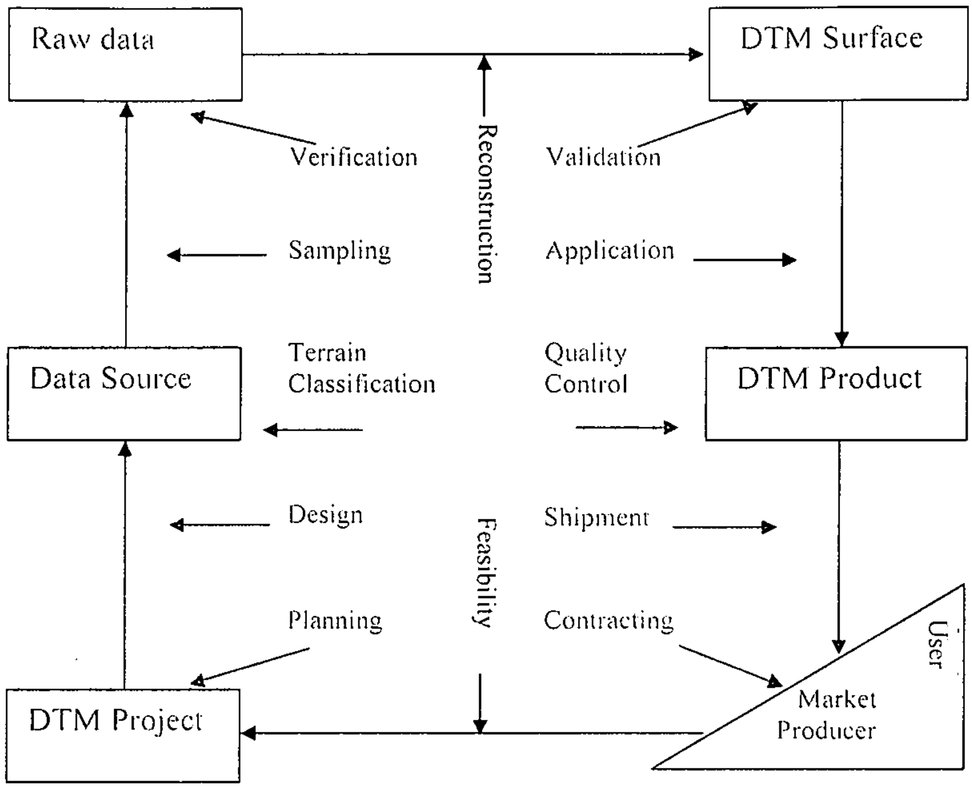


Figure 2.3 Process of digital terrain modeling [6].

2.3 DTM Data Collection Techniques

Digital terrain modeling is based on topographic information that can be obtained by; aerial photogrammetry, satellite-based radiometer or optical imaging, radar interferometry or the so-called interferometric Synthetic Aperture Radar (InSAR, Light Detection and Ranging (LIDAR), cartographic digitization and also land surveying [6]. Photogrammetry, remote sensing, SAR and cartographic digitization are usually used for generating low to medium resolution DTM. LIDAR, classical and GPS surveying is commonly employed for generating medium to high resolution DTM [7].

2.3.1 Aerial photogrammetry

Photogrammetry has the longest history amongst other DTM generation technologies. As mentioned before, in the beginning of DTM development, it was the major technique of DTM acquisition [6]. The generation of DTM using photogrammetric principles has two operational parts: firstly to the measurement phase, and secondly the derivation of the DTM [10]. The main data source is aerial photograph (digital or analog). The DTM is derived from a stereo pair of aerial photos based on feature matching. This process requires Ground Control Points (GCP), a set of points used for the tie point reference between photos.

2.3.2 Optical and radiometric remote sensing

Satellite imaging or remote sensing is pretty similar to aerial photogrammetry in many ways. The basic fundamental differences between them are the sensor and the platform used for the techniques that is scanner and camera respectively. Hence, satellite image-based DTM generation is somehow alike to photogrammetry DTM generation which requires two overlapped images. These two images can be acquired either at the same time by using two separate antennas mounted on the platform, or acquired separately in time by re-visiting the scene with a single antenna. The successful processing of these images depends on the sun illumination and cloud covering conditions [9].

2.3.3 Synthetic aperture radar

Synthetic Aperture Radar (SAR) is a side-looking active radar-ranging system [8]. It uses the microwave portion of the electromagnetic spectrum, encompassing frequencies in the range 0.3GHz to 300GHz (wavelength 1m to 1mm). InSAR requires two SAR images acquired over the same scene. The two images are then co-registered precisely to each other so that the phase difference between the pixels in the two images can be calculated. This phase difference, or so-called *interferogram*, can be used to derive the DTM of the imaged area [10].

2.3.4 Light detection ranging

Light Detection Ranging (LIDAR) provides height accuracies ranging from 0.1–0.5m and horizontal accuracies ranging from 0.3-1.5m [26] Data collection can be performed either from airborne laser profiling and terrestrial laser scanning. In the airborne laser profiling, data are collected by the laser scanner mounted on the airplane as a stream of discrete reflected laser points from the ground. At least two recordings, the first and last received signals, of each of the reflected laser points are recorded. By determining the difference between the two received signals, the height of objects such as trees or buildings can also be measured. The accuracy of using this technique for DTM generation is dependent upon the properties of the terrain. In the cases of hilly or flat terrain densely covered by vegetation, accuracies tend to decrease [27].

2.3.5 Cartographic digitization

This is the technique of acquiring DTM by digitizing available maps. This can be done either manually or by automated devices or softwares. Tablet digitizer is an example of truly manual and analog line following digitization. On screen digitization using CAD software is the example of manual line following digitization. For the latter, the map needs to be scanned first using raster scanner devices. Data obtained by digitization are in digitizer coordinate system and commonly transformed into geodetic system using set of control points extracted from map grid or GPS observation data. The accuracy of the DTM generated by this method highly depends on the accuracy of the source map and the process of digitization [6].

2.3.6 Classical land surveying

Classical land surveying is the most common technique used in civil engineering projects. Data collection is commonly performed using analog or electronic theodolites or total station with trigonometric leveling methods [6]. It can also be performed by differential level using baseline and cross-section method. This method requires at least two persons to do the survey, one for operating the instrument and another one for holding the target (prism pole, staff, etc). Classical land surveying is still widely in use and capable of giving high accuracy up to millimeter level [5]. In term of efficiency, this technique is more labor intensive and suitable for high-resolution DTM covering small area [6]. The major drawback of this technique is the requirement of intervisibility between the equipment and the target, as well as between the occupation point and the backsight. Beside, it is unlikely to do this survey during rainy weather. These conditions frequently slow down the speed of survey which typically leads to data collection cost inflation.

2.3.7 Global Positioning System

Global Positioning System (GPS) technique is varied in term of specification, capabilities, and accuracies. Code phase measurement offers accuracy ranging from sub meter until 50 meter [28]. Carrier phase data processing provides accuracy ranging from sub centimeter until sub meter. Illustration of GPS techniques, its applicability, and accuracy is given in Figure 2.4.

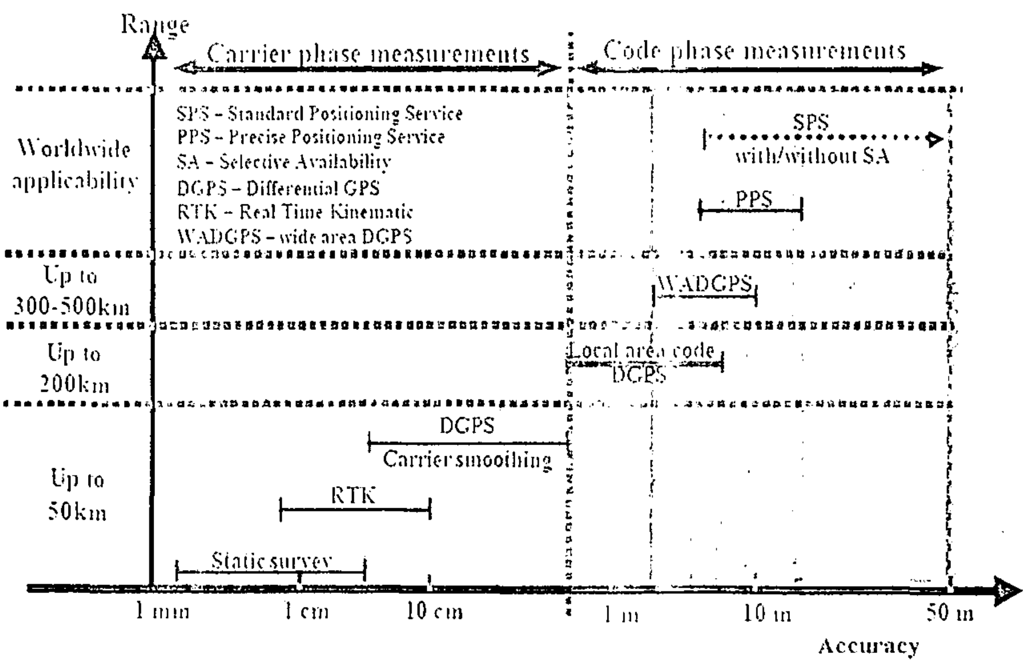


Figure 2.4 GPS techniques [28].

Static GPS technique (stop and go, fast static or rapid static) have been employed for establishing control point for deriving DTM from aerial photos or satellite images and testing DTM quality [12]. It also has been used for generating DTM and determining local geoid solution (reference height approximated by earth's gravity or by Mean Sea Level) [13, 29, 30]. Kinematic GPS technique has been employed for DTM data acquisition and capable of giving centimeter level of accuracy [7, 13]

All the above techniques are based on differential GPS. This requires at least two simultaneous data collected by different receivers. These data needs to be processed using either commercial or scientific software to produce proper accuracy respective to the used application as shown in Figure 2.4. This is particularly the drawback of static and kinematic GPS techniques where more time needed on the processing phase. Besides, for static positioning, the data collection process is also relatively slow in term of survey speed. Minimum observation for rapid static is 5 minutes for baseline length less than 5 km. While for baseline length above 5 km and up to 20 km the observation period is recommended to be extended up to 20 minutes for 20 km baseline.

2.4 Real Time Kinematic GPS for DTM Data Collection

The Real Time Kinematic (RTK) GPS method is a differential positioning technique that uses known coordinates of a reference station occupied by one receiver to determine coordinates of unknown points visited by other receiver called rover receiver [31].

2.4.1 RTK GPS concept

Similar to static GPS, the RTK GPS reference station is set on a point of known coordinates but the use of a data link to transfer measurements acquired at the reference receiver to the roving receiver, permits real time calculation of the rover coordinates. In the beginning of every RTK session, both reference and rover receivers must undertake an initialization procedure. This procedure uses a process called double differencing. Double differencing is used to assist the computation of the unknown number of wavelengths between a satellite and the receiver at the moment of the first simultaneous measurement of both GPS receivers. This process is known as "ambiguity resolution" [14]. As shown in Figure 2.5, this is done by forming (a minimum) of four pairs of satellites where the receivers count the whole number of wavelengths from each satellite to eliminate the largest error sources, specifically satellite and receiver clock bias.

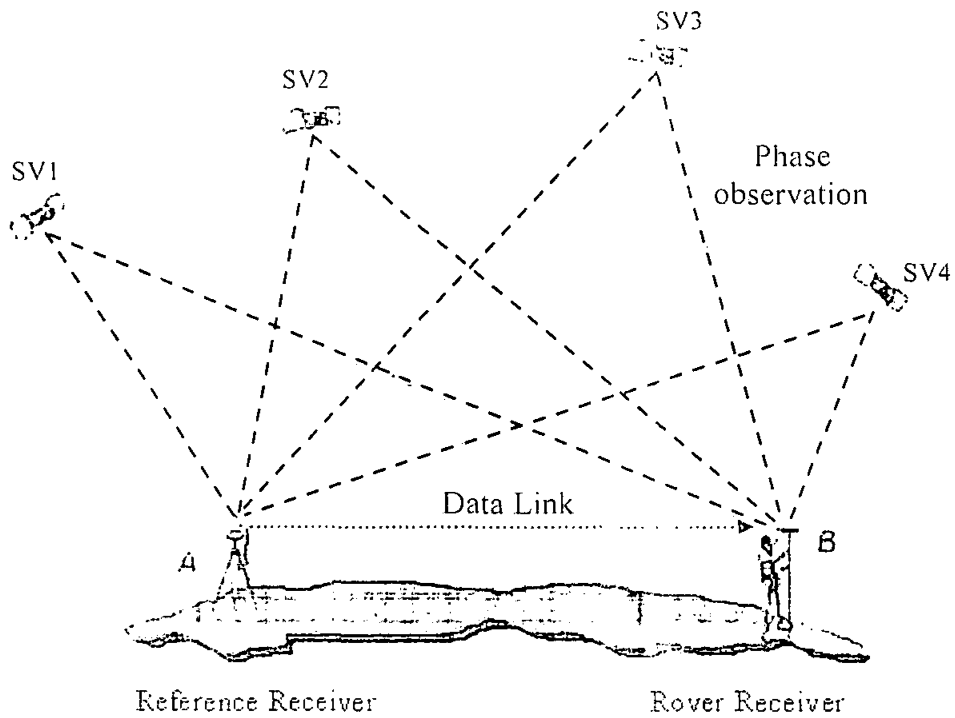


Figure 2.5 RTK GPS concept [32].

Once successful initialization has been performed and ambiguities have been resolved, the rover receiver produces centimeter level positions with respect to the base station receiver. The rover receiver is then can be used for 3D coordinates data collection. Any loss of lock on the satellites will require the receivers to undergo this initialization procedure again. The process of re-acquiring data on a certain point following a re-initialization procedure is called re-occupation [14].

2.4.1.1 RTK ambiguity resolution

RTK Ambiguity resolution can be carried out by static initialization, occupying a known station, or by the On The Fly (OTF) approach. The latter has become a standard approach since it requires less operator interference and can be applied whether the receiver is static or in motion. The level of success of the OTF ambiguity resolution approach is a function of the number and geometry of the satellites observed, the quality of measurements, the reference-to-rover distance, and the impact of measurement errors (ionospheric and multipath errors). The more satellites to be included in ambiguity resolution, the higher the percentage of finding the correct ambiguities, and the faster the resolution can be resolved [33]. For short distances, the ambiguities can be solved in less than one minute if five satellites or more are being observed.

Among the mainly used approaches for ambiguity resolutions are: the Ambiguity Function Method (AFM), the Fast Ambiguity Resolution Technique (FARA), the Least-squares AMBiguity Decorrelation Adjustment (LAMBDA), and the null-space method. The LAMBDA method is broadly adopted for OTF ambiguity resolution as it distinguishes from the other methods in the sense that when the resolution or adjustment is concluded with a complete or partial vector of integer ambiguities (a), it is guaranteed that this vector minimizes the integer least-squares criterion $(a' - a)^T Q\text{-}1\ (a' - a)$, with a' the vector of float ambiguities, and Q its variance-covariance matrix [31]. The linearized system of the LAMBDA method can be given as [34]:

$$\mathrm{Y} = A\,a + B\,b + c \tag{2.1}$$

where:

Y = observed vector minus computed double differencing carrier phase measurements,

a = vector of unknown integer double differencing ambiguities,

b = vector that contains the increments of the unknown baseline components;

A, B = are the design matrices for ambiguity terms and baseline components, respectively;

c = is the vector of measurement noise and un-modeled errors.

2.4.1.2 RTK data link

The data-link specifications are a function of quantity of data to be transmitted (number of satellites, data type and format), reliability and integrity requirements, operating conditions, and distance between the reference and remote stations [31]. Ultra High Frequency (UHF), Very High Frequency (VHF) or spread spectrum radios are currently the commonly used types of data links. Data transmission is also feasible using cellular phones employing special modems such as using Global System for Mobile Communications (GSM) technology. Nevertheless, at present, this is highly limited to the network coverage RTK systems and prone to latency issue. RTK GPS data are usually transmitted using the Radio Technical Commission for Maritime Services Commission (RTCM) SC-104 version 2.1 and 2.2 format, transmitting principally message types 18 and 19, which contain the raw phase and code measurements, respectively. Some manufacturers utilize a more concise RTK data format as an alternative to RTCM, mostly to reduce bandwidth requirement and data latency. Examples are the Compact Measurement Record (CMR) used by Trimble and Topcon, and the Binary Data format employed by Ashtech [31].

2.4.1.3 RTK GPS receivers

Besides dual frequency receiver, single frequency receiver could also be used for RTK. Nevertheless, for long reference-to-rover distances dual frequency receivers are preferred for faster acquisition of correct ambiguities. In practice, fixing the integer ambiguities using single frequency receiver is somewhat difficult and prone to a float solution, which commonly leads positioning accuracy decrease to decimeter level [31]. This problem is not valid with dual frequency systems, where fix solution is commonly possible for short to medium distances (less than 15 km), giving an accuracy at the cm level. A combined GPS and *Global'naya Navigatsionnaya Sputnikovaya Sistema* (GLONASS) RTK system in single frequency is nearly on a par with GPS dual frequency system for fixing the ambiguities, on condition that enough GLONASS satellites are available. However, once distance increases, a dual frequency RTK system performs better [35].

2.4.2 RTK GPS in DTM data collection

Real Time Kinematic (RTK) GPS is frequently used as a verification reference for DTM derived from photogrammetry, remote sensing, and interferometric radar as well as synthetic aperture radar [10]. This is commonly done by assessing the discrepancy between profiles extracted from DTM or DEM and profiles measured by RTK GPS technique [10].

A preliminary study on practical issues in the use of RTK GPS for 3D mapping has been performed [36]. It was done by collaborating RTK GPS and Total Station for 3D mapping in an urban area. The former was for surveying the features with open-sky condition such as parking lot, slopes and flyover. The latter was for establishing traverse stations and surveying spot levels and other obstructed features like buildings (roof top was not accessible) and roads under flyover. The accuracy assessment was based on the standard of large scale mapping of 1:1000 where the horizontal and vertical accuracy thresholds are 0.2m and 0.3m respectively. This collaboration technique was proven to be efficient.

Yilmaz et al [37] conducted an experimental study of DTM data collection using RTK GPS. The DTM was generated from a regular grid data and interpolated using Kriging algorithm. The DTM was verified by defining cross sections over the generated DTM and comparing the height result given by RTK GPS based DTM and conventional survey (EDM complemented with level) based DTM. The height was interpolated from the neighboring contour lines of each DTM. This verification is bias since it is difficult to recognize error source of the discrepancy where it could be contributed by the measurement or the interpolation it self. Furthermore, sky view and situation of the surrounding has not been addressed. This description and details of the environment of the study area are vital where RTK GPS performance is commonly correlated with these.

2.4.3 Possibilities and limitations

Applying RTK GPS for DTM data collection requires assessment of some possibilities and limitations especially due to the issue of GPS heighting [38]. It typically involves measuring ellipsoidal heights with GPS, applying some form of geoid model and making any adjustment to fit the resulting heights to the existing vertical datum. There are three major factors related to this; accuracy of GPS measurement, availability and accuracy of geoid model, and vertical datum issues. These factors vary in importance depending on application. GPS surveys over national scale are typically correlated with datum issues and need more consideration than day to day surveys which extend over a few kilometres or less [38].

Commercial RTK GPS products available in the market offer centimeter accuracy of real time 3D positioning. Each product has their own specific accuracy claim by their respective manufacturer. However, in general, most dual frequency receivers' accuracy is ranging from 1-2cm ± 1-2ppm for horizontal positioning and 1.5-5cm ± 1-4ppm for vertical positioning. The ppm (part per million) sign that the constant accuracy value will be added by certain value of error proportional to the length of the baseline (distance between reference and rover) is given in Table 2.1. The accuracy of single frequency receivers is commonly lower when compared to the dual frequency of the same respective manufacturer [38].

Table 2.1 Accuracy of RTK GPS techniques [38].

Mode	Accuracy		Error in mm (1 sigma)			Error in mm (3 sigma)		
	mm	+ ppm	1km	5km	10km	1km	5km	10km
RTK GPS 1Hz	20	2	22	30	40	66	90	120
RTK GPS 5Hz	50	2	52	60	70	156	180	210

Note: unit of errors are in mm

It must be underlined that the issues and accuracy values outlined above are only for the GPS measurements capability. For day to day surveys over project areas below 10km in scope, the GPS measurement is the least significant part of the GPS heighting. The high productivity of RTK with its ability to yield real time 3D position with centimeter level accuracy has attracted a growing interest. This leads surveyors to employ the technique for height measurements required in engineering applications. Nonetheless, some caution is required and it is necessary to consider how RTK errors increase with baseline length using a particular equipment configuration. For DTM data collection requiring height accuracy at the several centimeters level, RTK may well be suited. For more precise engineering surveys, however, where the heighting accuracy required is at one centimeter level, RTK may be suitable but suppose to be restricted to baselines shorter than a kilometer [38]. In support of projects extending more than a kilometer, several RTK base stations may be required. Another technique of improving the accuracy of RTK over longer baselines is to observe for longer periods at a point [14].

For projects extending over many kilometres the issues of geoid and local vertical datum distortion will need to be considered [38]. Various systems allow incorporation of geoid models into the real time data processing. Nevertheless, that assumes any local distortions are integrated in the geoid model to an accuracy adequate for the project. In practice then, when contemplating RTK for centimeter level GPS heighting, it is necessary to develop field procedures that examine all possible error sources. Such procedures also need to be flexible and assessed on a case by case basis.

2.5 Terrain Surface Sampling Strategy

Terrain surface comprises an infinite number of points. Therefore, full information of terrain surface is unattainable since it is impossible to measure all those infinite number of points. Hence, terrain surface is commonly represented by a set of finite points. In fact, for most cases, complete information about terrain surfaces is not required as it is necessary only to collect adequate data points to meet the degree of accuracy and fidelity of the model [6]. The process of selecting points to be measured in certain manner is called sampling. The problem here is how to sufficiently represent the terrain surface by a limited number of points. This is why point sampling strategy is essential in digital terrain modeling.

2.5.1 Selective sampling

Selective sampling is well suit for land surveying. In this technique, data collection is performed through the most important points or features. Additional points between features are also collected to gain certain density [6]. The advantage of this technique is that fewer points can represent the surface with high fidelity.

2.5.2 Contouring and profiling

Contouring and profiling are a one dimension fixed sampling. The term contouring denotes that the data sampling is along contours. This is typically employed in photogrammetry. In contouring, the height value (Z) is fixed. If the fixed dimension is X, and the sampling is performed through YZ plane, so the result is a profile of the YZ plane. The process to obtain a profile is called profiling [6]

2.5.3 Regular grid and progressive sampling

Regular grid sampling means that data are collected in the form of a regular grid with certain fixed interval in both X and Y directions [6]. Heavy redundancy is required to ensure that the topography changes are represented in a proper manner. This is the pitfall of regular grid sampling. Progressive sampling is commonly applied to resolve the redundancy problem. In this method, the sampling is performed in a grid pattern whose interval changes progressively from coarse to fine over an area.

2.5.4 Composite sampling

Composite sampling is carried out by combining selective sampling and regular grid sampling. Selective sampling is effective in the terrain representation meanwhile regular grid sampling is efficient in measurement. Hence, composite sampling furnishes greater advantages. In this technique, abrupt changes or specific features on the terrain such as breaklines, ridges, and depressions are sampled selectively. Meanwhile, plain area, hollow, and other continues surfaces are sampled with regular grid.

Sampling operation is defined by two parameters, distribution and density. Distribution is described by location and pattern. Location is defined in 2D positional coordinates. It is commonly represented by latitude and longitude in geographic coordinate system or easting and northing in grid coordinate system. Meanwhile pattern of the sampled data could be collected in various ways. Figure 2.6 gives the classification of sampled data patterns. The accuracy of sampled data highly depends on the measurement method such as the mode of measurement, the instrument, and adopted technique.

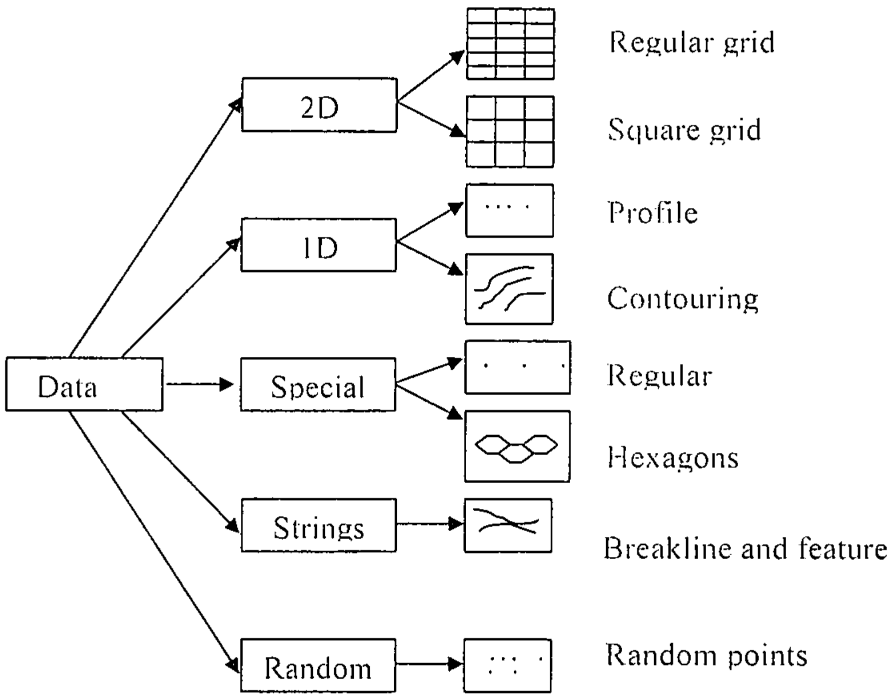


Figure 2.6 Pattern of sampled data points [6].

Density is specified by measures like the distance between two points or sampling interval, the number of points per unit area, the cut-off frequency, etc.

2.6 Approaches of DTM Processing

A Digital Terrain Model is a mathematical model of terrain surface. These mathematical functions/polynomials are usually referred to as interpolation. In general, there are several mathematical functions used in terrain modeling as shown in Table 2.2. Each polynomial function has its own characteristics. A terrain surface with unique characteristic can be constructed by using specific function. The lower order polynomials are suitable for relatively flat terrains while the higher order will fit complicated or hilly terrains [6].

Table 2.2 Polynomial function for terrain modeling [6].

Polynomial Function	Order	Descriptive Terms	No. of Terms
$Z = a_0$	Zero	Planar	1
$Z = a_0+a_1X+a_2Y$	First	Linear	2
$Z = a_0+a_1X+a_2Y+a_3X^2+a_4Y^2+a_5XY$	Second	Quadratic	3
$Z = a_0+a_1X+a_2Y+a_3X^2+a_4Y^2+a_5XY+a_6X^3+a_7Y^3+a_8X^2Y+a_9XY^2$	Third	Cubic	4
$Z = a_0+a_1X+a_2Y+a_3X^2+a_4Y^2+a_5XY+a_6X^3+a_7Y^3+a_8X^2Y+a_9XY^2+a_{10}X^4+a_{11}Y^4+a_{12}X^3Y+a_{13}X^2Y^2+a_{14}XY^3$	Fourth	Quartic	5
$Z = a_0+a_1X+a_2Y+a_3X^2+a_4Y^2+a_5XY+a_6X^3+a_7Y^3+a_8X^2Y+a_9XY^2+a_{10}X^4+a_{11}Y^4+a_{12}X^3Y+a_{13}X^2Y^2+a_{14}XY^3+a_{15}X^5+a_{16}Y^5+a_{17}X^4Y+a_{18}X^3Y^2+a_{19}X^2Y^3+a_{20}XY^4$	Fifth	Quintic	6

Digital terrain modeling approach can be categorized by the basic geometric unit used for the modeling. As shown in Figure 2.7, there are four types of approaches that are; point-based, triangle-based, grid-based, and hybrid modeling.

2.6.1 Point-based modeling

In this approach, terrain modeling is constructed from a series of sub-surfaces based on the height of individual points. It makes use zero order planar surfaces to represent small area around data points. The whole DTM is formed by a series of contiguous discontinuous surface. Point based modeling is a simple approach but having the drawback of discontinues surface representation. The only difficulty is to define the boundaries between adjacent areas.

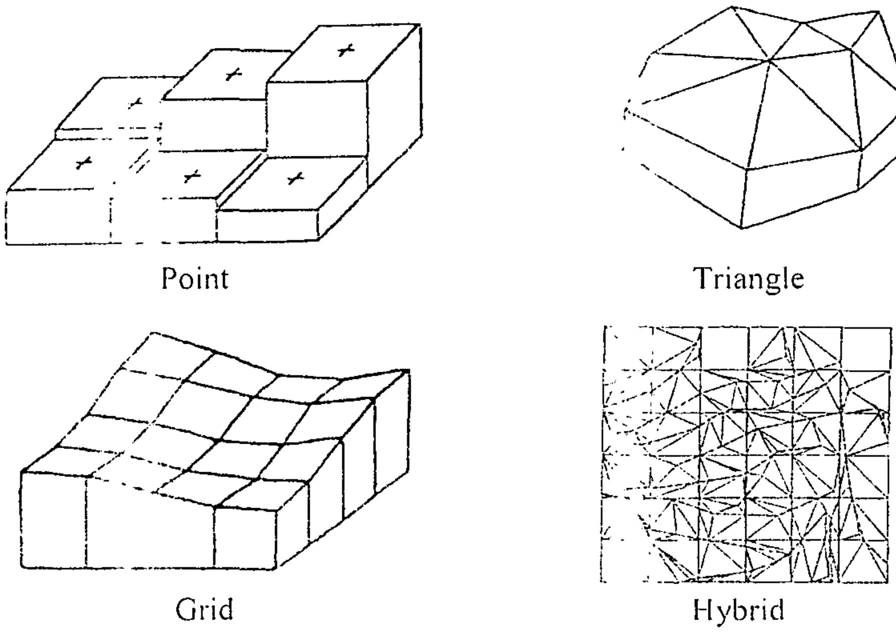


Figure 2.7 Approaches of digital terrain modeling [6].

2.6.2 Triangle-based modeling

Terrain modeling is constructed by a linked series of continuous contiguous triangles facets called TIN (Triangular Irregular Network) [6]. TIN can be generated by many criteria. Delaunay triangulation is the most familiar criterion in triangulation. It has the property that there are no other data points inside the circumcircle of every triangle. As a Delaunay triangulation maximizes the minimum angle of a triangulation, the triangles are relatively compact [7]. The triangle is regarded as the most basic unit in all geometrical patterns. It has a good flexibility to incorporate breaklines, formlines, and other data. High order polynomial may also be applied to construct curved facets which will give better representation of terrain surface [6]. Hence, triangle based approach has been widely used in terrain modeling and is regarded as the main approach to terrain modeling.

2.6.3 Grid-based modeling

Terrain modeling is constructed from a linked series of bilinear surface. As shown in Table 2.2, it uses the first three term together with the term a_3XY of the general polynomial which requires in minimum of four data points. The bilinear surface is also called as grid. This grid can be in a shape of parallelograms, rectangles or squares. Regular square grids are the most suitable pattern. This is due to some practical reason such as simple data structure and the ease of surface representation. High order polynomial may also be used in grid based modeling. Nevertheless unpredictable oscillations in the resulting DTM surface might occurs if too many terms of the polynomial are used [6]. Hence, usually only second and third order are used.

2.6.4 Hybrid modeling

A complex DTM surface is usually constructed from one or two main types of network. Network is referred to as the actual data structure implemented using a particular geometric pattern for terrain modeling that is grid or triangular. Nonetheless, a hybrid approach is also widely used to construct DTM. It is referred to as an approach which is constructed by both grid and triangular network [6]. Hybrid modeling must have a basic grid of squares or triangles obtained by systematic grid sampling. As an example, if breaklines and formlines are available for inclusion, regular grid is broken into triangles and a local irregular triangular network is implemented. It is also possible to combine point based, grid based, or triangular based modeling together to form a hybrid approach. Technically, hybrid based modeling is the combination of the three previous mentioned approaches. It is effective for terrain modeling and conforms well to our subjective interpretation of what a real terrain should look like.

2.7 Quality Measures of DTM

A DTM is a 3D representation of terrain surface where some errors might occur in each of the three dimensions of the spatial coordinates (X, Y, and Z). X and Y are combined to give a planimetric (horizontal) error while the third is in the Z direction and referred to as elevation (height) error [6]. The process of DTM accuracy assessment can be carried out in two different modes. The first one is by assessing the planimetric accuracy and the vertical accuracy separately [6]. The second one is by assessing both simultaneously [6].

2.7.1 Approaches for DTM accuracy assessment

According to Ley [39], there are four possible approaches for assessing the vertical accuracy of the DTM;

i. *Prediction by production (procedures)*: This is to asses the likely errors introduced at the various production stages together with an assessment of the vertical accuracy of the source materials.
ii. *Prediction by area*: This is based on the fact that the vertical accuracy of contour lines on a topographic map is highly correlated with the mean slope of the area.
iii. *Evaluation by cartometric testing*: This is concerning experimental evaluation. For such a test, a set of checkpoints is required.
iv. *Evaluation by diagnostic points*: A sample of heights is acquired at the time of data acquisition and this set of data is used to check the quality of the model. This can be performed at any intermediate stage as well as the final stage.

Theoretically, there are three approaches for assessing planimetric accuracy of DTM [39], namely;

i. *No error*: It is argued that a DTM provides use of set heights with planimetric accuracy positions, which are inherently precise.
ii. *Predictive*: Similar to the prediction by area used for vertical accuracy.

iii. *Through height*: To fix the positions of node heights by comparing a series of points.

However, as also mentioned by Ley [39], it is difficult to bring these into practice. Hence the issue of planimetric accuracy is infrequently addressed. Such an alternative approach is to simultaneously assess the vertical and horizontal accuracies. However there is no consensus and many authors follow the practice of assessing the vertical accuracy only [5, 6, 15].

2.7.2 Measures for DTM accuracy

Let $f(x, y)$ be the original terrain surface and $f'(x, y)$ be the constructed DTM surface, then the difference, $e(x, y)$, where:

$$e(x, y) = f'(x, y) - f(x, y) \tag{2.2}$$

is the error of the DTM surface. Correspond to this, Meneses et al [5] stated that the mean square error (mse) can be used as a measure for DTM accuracy, where:

$$\text{mse} = \iint e^2(x, y)\, dxdy \tag{2.3}$$

$e(x, y)$ is a random variable in statistical term [6]. Magnitude and dispersion are the two characteristics of random variable. Some parameters that can be used to measure the magnitude of random variable are; extreme values (e_{max} and e_{min}), mode (most likely value), median (the frequency center) and mathematical expectation (weighted average). Meanwhile, some parameters that can be used to measure the dispersion of random variable are; range, expected absolute deviation and standard deviation.

Hence, in addition to the mse, the following parameters are also commonly used to measure DTM accuracy [6, 40]:

$$R = e_{max} - e_{min} \tag{2.4}$$

$$E_m = \frac{\sum e_i}{u} \tag{2.5}$$

$$\sigma = \sqrt{\frac{\sum (e-\mu)^2}{u-1}} \tag{2.6}$$

where R is range, E_m is mean; e_i is the value of error of each sample, u is the number of the sample, σ is standard deviation and μ is the average.

The use of range may refer to a specification of DTM accuracy as like the US National Map Accuracy Standard. However, some characteristic of this measure might be objectionable, that is;

i. The value of range depends only on two values of the random variable
ii. The probability of the values in $e(x, y)$ is ignored

Hence, the combination of mean and standard deviation is preferred although the distribution of DTM errors is not necessarily normally.

2.7.3 Volumetric accuracy analysis

The volumetric accuracy analysis has been conventionally used in civil engineering. This criterion was introduced given the economic importance that the control of volume measurements plays in civil engineering projects. The consequence of this method is the need for a reference model which has reliable quality [5]. Accuracy estimation based on DTM volume comparison is simple, however could present a global DTM quality measure [3, 15].

Volumetric accuracy analysis can be performed by analyzing the excavated (negative difference) and embanked (positive) areas. This is done by defining a plane on certain height of the DTM and calculating the respective volumes [5].

2.8 Summary of the Literature Review

From these literatures review, it can be seen that, most of the work in the area of digital terrain modeling is focused on three parts. The first part is the DTM data collection, where many author support the finding that this is the most important part of digital terrain modeling. Each data collection technique has it own merits and pitfalls. Main criteria that have to be considered in selecting the most suitable technique, with respect to scale of the application is; accuracy, speed of survey, cost, ease of use and repeatability. Photogrammetry and remote sensing are commonly applied on the generation of medium to low-resolution DTM. Meanwhile, laser scanning and land surveying (TS and GPS) are usually employed for high-resolution DTM generation. Several preliminary studies and experiments on the application of RTK GPS for DTM data collection have been conducted. Nevertheless, many of those studies were based on combining TS and RTK GPS for 3D coordinates data collection. A pure RTK GPS survey for high resolution DTM data collection has not been investigated. Furthermore, quality measure of DTM generated from RTK GPS data has not been properly addressed. The second part is the DTM processing. Among four main approaches that has been commonly used, TIN is preferred for high resolution DTM generation since it has a good flexibility to incorporate breaklines and formlines which is very useful for reconstructing structural features and abrupt changes. While, grid based algorithm is better to be used for producing continuous surface. The third part is the DTM quality measure. This is also an essential part of digital terrain modeling, since one of the important factors that should be considered in using DTM is the quality characterization of the DTM itself. This is a particularly relevant issue where, as well as the technical inferences, a lack of quality in the DTM can lead importance economic deviations during project execution.

CHAPTER 3

METHODOLOGY

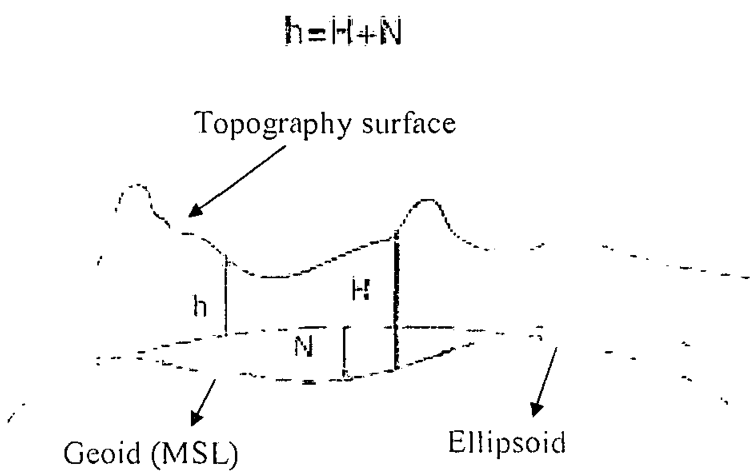
3.0 Introduction

This chapter describes the details of the experimental research on digital terrain modeling by using Real Time Kinematic GPS (RTK GPS) data. The experiment presented on this work is based on the comparison of RTK GPS against Total Station (TS) as a means of DTM data collection. Generally, the comparison covers the efficiency, productivity, and accuracy assessments. This work is intended to deliver a comprehensive understanding that RTK GPS can provide an easy, accurate, comparatively productive and efficient alternative for high resolution DTM data collection.

In spite of using local coordinate system, the DTM presented in this work uses a global coordinate system based on Universal Transverse Mercator (UTM) projection. The use of the coordinate system is to enable the data to be used for other application such as for Geographical Information System (GIS) where coordinated DTM on a certain system is mostly needed [41]. Besides, the use of the coordinate system allows easy transformation into other coordinate system when required.

The UTM system divides the surface of the earth between 80° S latitude and 84° N latitude into 60 zones, each 6° of longitude in width and centered over a meridian of longitude. Zones are numbered from 1 to 60. Each of the 60 longitude zones in the UTM system is based on a Transverse Mercator projection. The study area which is inside the campus of Universiti Teknologi PETRONAS is located on zone 47N (N here stands for north hemisphere).

It might be ubiquitous, but it is necessary to discuss about the height reference. The GPS uses height (h) above a reference ellipsoid that approximates the earth's surface; defined by semi major axis, semi minor axis, and flattening. This is called the geometric height. While, the conventional land surveying uses the orthometric height. Orthometric height (H) is the height above an imaginary surface called the geoid, which is determined by the earth's gravity and approximated by Mean Sea Level (MSL). The signed difference between the two heights (the difference between the ellipsoid and geoid) is the geoid height (N) or known as geoid undulation [30]. The illustration is given in Figure 3.1.



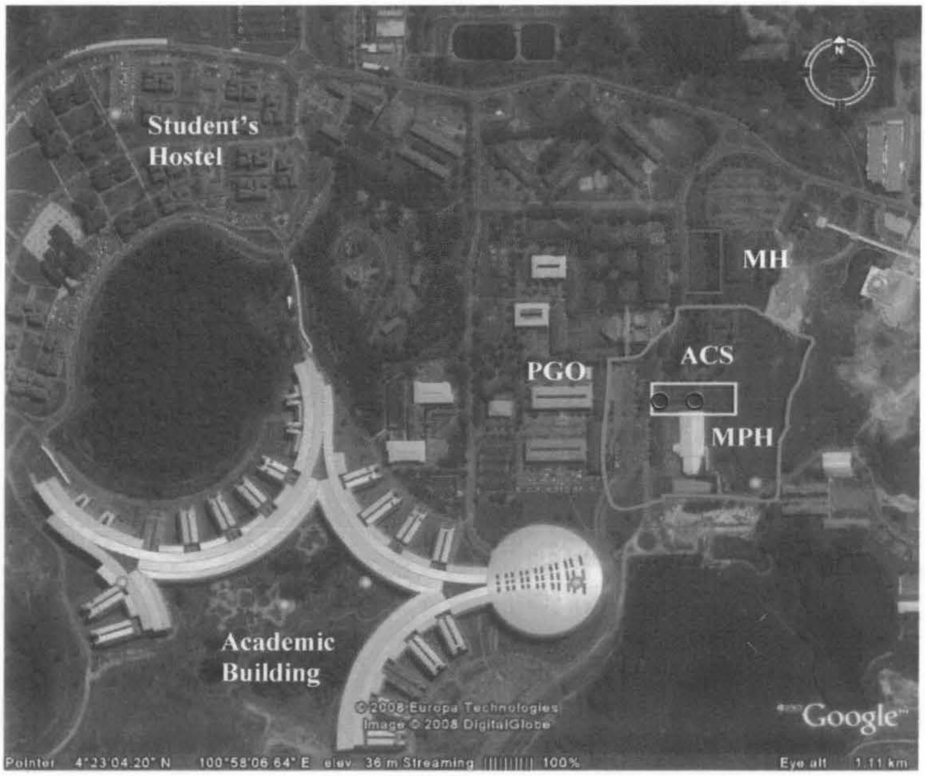
H: orthometric height
h: geometric height
N: geoid height

Figure 3.1 Height references.

The application of the DTM designed in this work is for large scale projects where it usually covers relatively small area (radius below two kilometers) [38]. For this particular area, the geoid undulation can be considered to be constant [31, 38]. Consequently, although the value of the geometric and orthometric height may be different, but the height difference is approximately equal. In this work, both of the RTK GPS and TS uses the same initial height provided by existing benchmark on Universiti Teknologi PETRONAS campus.

3.1 Study Area Description

DTM data collection was carried out at several portions of campus area of Universiti Teknologi PETRONAS (UTP) as shown in Figure 3.2. UTP campus is built on a 400 hectare (4000000m^2) site and strategically located at Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia.



Note:

Terrain-1

Terrain-2

Terrain-3

Benchmark

Figure 3.2 Study areas inside Universiti Teknologi PETRONAS campus (satellite image taken from Google Earth^{TM})

As shown in Figure 3.2, there are three different study areas with specific characteristics of terrain surfaces, topographic features, as well as sky view of the surrounding.

a) Terrain-1

Terrain-1 covers the parking lot and open area in front of Postgraduate Office (PGO), fair slope on the eastern side of Academic Central Services (ACS) and the area on the surrounding of Multi Purpose Hall (MPH). It is a complex terrain characterized with various structural features such as; road, drainage, retaining wall, etc. The sky obstructions on this area are mostly contributed by building and various vegetations throughout the area. The whole size of the area is approximately 62500m^2. Referring to the size of the area, DTM data acquisition of Terrain-1 can be consider as large scale application.

b) Terrain-2

Terrain-2 is located on the northwest of MPH. It is a portion of the Terrain-1. It is characterized by fair slope grass-land. The size of the area is around 6400m^2. The obstruction is contributed by trees and few buildings on the northern and western side of the area.

c) Terrain-3

Terrain-3 is located on the western side of Main Hall (MH). It is characterized by relatively flat terrain with steep slope on the western part of the terrain. The size of the area is about 6300m^2. The obstruction on this area is considered to be rather high where nearly half of the area is covered by various vegetations.

The pictures of the study areas (Terrain-1, Terrain-2 and Terrain 3) can be seen in Figure 3.3.

Terrain-1

Terrain-2

Terrain-3

Figure 3.3 Study areas.

3.2 Equipments and Apparatuses

The equipments and apparatuses used for the survey are as follow:

i. 2 units of RTK GPS: Topcon TPS Hiper, dual frequency receiver.
ii. 1 set Radio Modem (data link): Pacific Creast, Positioning Data Link (PDL), including 1 transmitter and 1 receiver antenna and interconnection cables.
iii. 1 unit Ranger Controller, including a connection cable.
iv. 1 unit Total Station: Topcon GTS 229.
v. 3 units of tripod
vi. 1 unit prism pole with mini prism reflector.
vii. 1 unit rover GPS pole
viii. 1 unit stick meter
ix. 2 units of external batteries
x. TS connection cable

The picture of the equipments used for the experiment is given in Figure 3.4. The specifications of the RTK GPS and the TS are available in Appendix A and Appendix B.

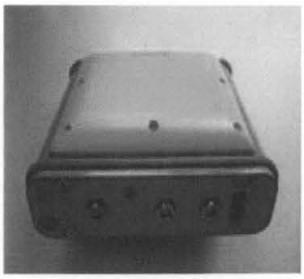
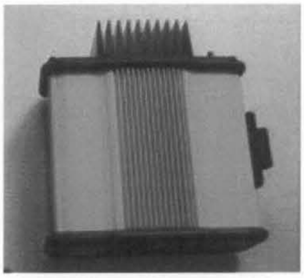
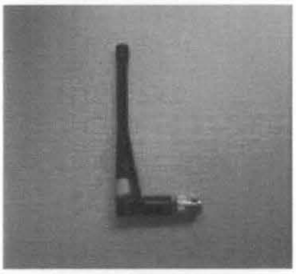
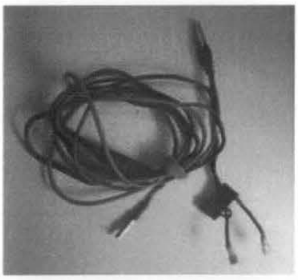
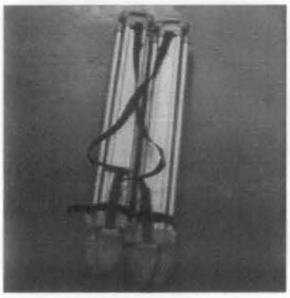
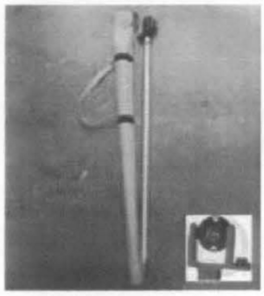
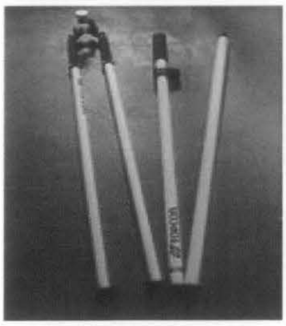
 GPS	 Radio Modem	 Transmitter Antenna
 Receiver Antenna	 Interconnection Cable	 Controller and Cable
 Total Station	 Tripod	 Prism Pole and Reflector
 GPS Pole	 External Battery	 TS Connection Cable

Figure 3.4 Survey equipments.

3.3 Equipment Testing

The RTK GPS receiver and TS used for the experiment has been tested. This is to assure that those equipments are still in good condition and capable of providing reliable data.

3.3.1 RTK GPS testing

The performance of RTK GPS receiver needs to be tested to assure that GPS-derived coordinates are uniformly high quality and fitting the accuracy as stated by the manufacturer. The test was carried out by the so called short baseline test [31]. As shown in Figure 3.5, the test was performed by measuring a short distance connecting two known points (benchmarks). Accuracy analysis of the RTK GPS receiver was performed by assessing the difference between the coordinates of the rover station measurements to the true value of the rover's known point coordinates [35].

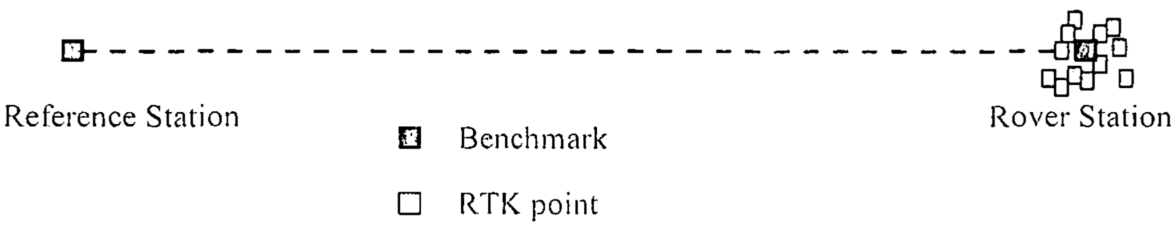


Figure 3.5 RTK GPS testing.

3.3.2 TS testing

The test was carried out by measuring certain distances between some JUPEM's calibration pillars, located at Batu Gajah, Perak [42] as shown in Figure 3.6. Each of the total station distance measurements was compared to the known distance between pillars that has been routinely measured and documented as the published true values.

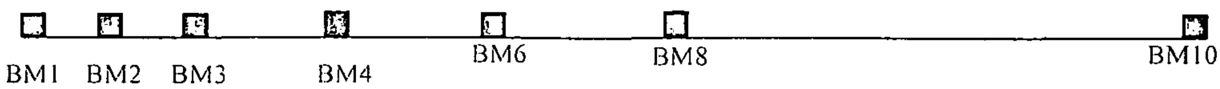


Figure 3.6 Distance measurement for total station testing.

3.4 Obstruction Survey

The obstruction survey was conducted in order to have an approximation of the average sky view of each terrain. Sky view is the level of sky clearness (free of obstruction such as; trees, buildings, etc) which commonly expressed in percentage [43]. The higher value of sky clearness, the better GPS signal can be tracked. The obstruction survey was performed using total station on several predefined spots of each terrain. It was carried out by measuring all obstructions on the surroundings of each spot. Each of the obstruction was defined by its bearing (from north) and its elevation. The data were then plotted in an obstruction diagram. An example of obstruction diagram is shown in Figure 3.7.

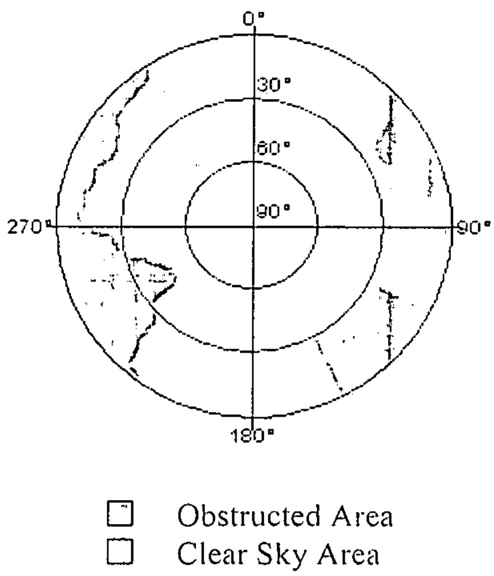


Figure 3.7 Example of obstruction diagram.

The total area of obstructions was calculated and then represented in a percentage with respect to the total area of the circle. The same procedure was repeated by plotting and calculating obstructions diagrams for the rest of the spots. Afterward, these diagrams were used to define the average sky view of each terrain.

3.5 DTM Data Collection

Besides creating a high resolution DTM, the other objective of this work is to assess the efficiency, productivity and accuracy of RTK GPS as a means of DTM data collection, compared to the conventional technique of land surveying using TS. In addition, an accuracy measure of the generated DTM is also required to characterize the quality of the DTM. To provide the basis for these, the DTM data collection was accomplished using two sampling techniques. The first is the DTM data collection using composite sampling, and the second one using grid-based sampling [6].

The DTM data collection using composite sampling was aimed for estimating the efficiency and productivity of RTK GPS technique. This was performed on Terrain-1 which has relatively large area size. The RTK GPS and TS survey was conducted under two constraints. Firstly, both of the surveys were carried out in the same duration of data collection. Secondly, it covered an equal area size. This was done to have a fair and valid efficiency and productivity comparison of those two techniques.

The DTM data collection using grid-based sampling was designed to accommodate the height error as well as volumetric error analysis to characterize the quality of the DTM [5]. This is particularly to study the effect of obstructions on the accuracy of RTK GPS data, and its influence to the quality of the generated DTM. This is an important issue, since generally; sky obstructions decrease the accuracy of GPS data. Both of the surveys used exactly the same survey grids. TS survey was used to establish the reference DTM to be used for the analysis.

Since the number of the collected data was exactly the same, efficiency and productivity comparison were also analyzed based on the total time needed to accomplish the survey. This grid-based sampling technique was applied for DTM data collection of Terrain-2, and Terrain-3. This is due to the significance difference of sky view of those two terrains.

3.5.1 DTM data collection by RTK GPS

Basically, RTK GPS survey requires two control points or benchmarks, one benchmark as its reference station and another one as its initial points [7]. This is particularly employed for projects where the survey execution requires more than a single session measurement.

The reference station is the place where we set the reference receiver. It is complemented with data link device which transmits the RTK GPS correction signal in real time to the rover receiver. The initial point is the benchmark that serves as a checkpoint of the RTK system. It has to be measured at the beginning of each RTK session. This is aimed to check the RTK system setup for any possible error that might occurs. The rover receiver is the mobile receiver which is used to collect data throughout the study areas.

In this work, the reference station was set at PG01 benchmark while the initial point was set at PP15 (see Figure 3.2). These benchmarks are located at Terrain-2, in front of UTP Postgraduate Office. The coordinates of those benchmarks in UTM system are as follow:

i. PG01 (Reference Station)
   Easting : 718718.515m
   Northing : 484880.681m
   Height : 26.705m

ii. PP15 (Initial Point)
   Easting : 718741.223m
   Northing : 484877.806m
   Height : 25.455m

The coordinates of the reference station (PG01) was used as the initial coordinates for the calculation of rover's RTK positions throughout the survey area. This coordinate calculation is called localization. Localization is the process of coordinate transformation from latitude-longitude format into easting-northing format using certain earth projection system. The RTK system calculation and information flow is given in Figure 3.8.

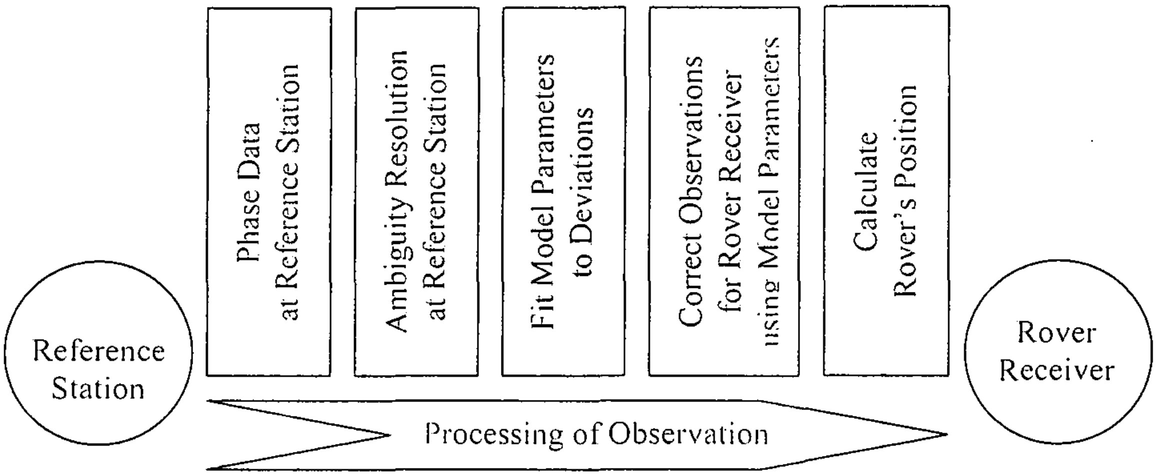


Figure 3.8 RTK system flows [44].

The ambiguity resolution is a function of the number and geometry of the satellites observed, impact of measurement errors, and the reference to rover distance. In general, for short reference-rover distances, the ambiguity can be solved less than one minute if five satellites or more are being observed [31]. Generally, ambiguity resolution of RTK GPS using differential carrier phase can be written as [45].

$$\nabla\phi\lambda = \begin{bmatrix} d & \lambda \end{bmatrix} \begin{bmatrix} X \\ n \end{bmatrix} + n_\phi \qquad (3.1)$$

with $\nabla\phi$ being the differential carrier phase, λ is the carrier phase, d is the vector between the GPS antenna and the satellites, X being the linearized position, n being the integer ambiguity, and n_ϕ being the differential phase noise plus the multipath error. Here, the process of defining the integer value of n is the basis of fixed RTK solutions which allows centimeter accuracy. Otherwise, if the value is not integer, the RTK solution is float. This will decrease the accuracy of RTK GPS solutions up to decimeter level. These integer estimates are then used to calculate the baseline (distance between the reference station and the rover station). The rover position is calculated based on the calculated baseline and the coordinates of the reference station. Equation 3.1 is the general formula of ambiguity resolution which commonly solved by linearization. As described in the previous chapter, the Least-squares AMBiguity Decorrelation Adjustment (LAMBDA) method is the main approach used by most current RTK GPS receivers.

The DTM data collection by RTK GPS was carried out by four main steps; setting-up reference station, setting-up rover receiver, initialization check, and data collection of topographic features.

3.5.1.1 Setting-up of the reference station

The GPS receiver was set up and centered on PG01 benchmark using a tripod and an optical-plummet tribrach. The radio modem was set-up close to the GPS receiver. It was connected to the GPS via data-link port. External batteries were used to power on the radio modem since it has no internal power supply unlike the GPS receiver. The ranger controller is then connected to the GPS via data-input port. The reference station setup is given in Figure 3.9. Following the completion of the setup process, the GPS receiver and radio modem were powered on and RTK system setting was started. The setting was performed using the ranger controller. This was including assigning the coordinate of the reference station and adjusting the RTK system properties. The main RTK properties that were adjusted are as follow:

i. Cut-off angle: 10°
ii. Minimum number of satellites in view: 5
iii. Maximum Dilution Of Precision (DOP): 6

The settings above are aimed to adapt the ease of conducting RTK GPS and in the same time also to maintain the reliability of the data [31]. The five minimum numbers of satellites in view is relatively easy to gain, however the quality control of the data can be preserved by the constraint of maximum DOP of six. DOP is a measure of the GPS receiver/satellite geometry [46]. A low DOP value (2, 3, and 4) indicates better relative geometry and higher corresponding accuracy. DOP value of six is the limit where the positional measurement is in survey-level accuracy [47].

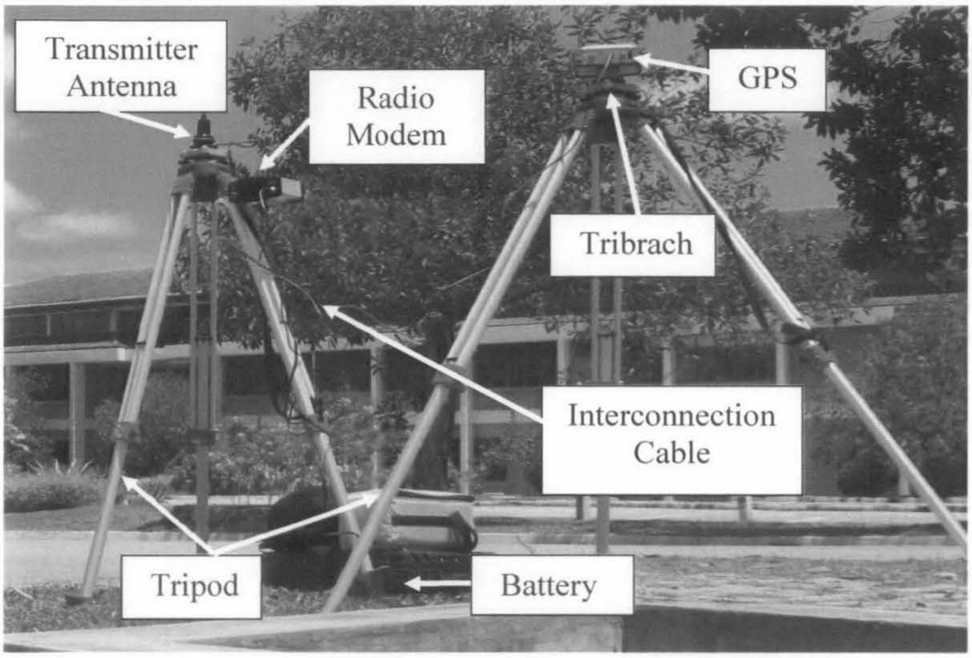


Figure 3.9 RTK GPS reference station receiver setup.

3.5.1.2 Setting-up of the rover receiver

The rover GPS receiver was mounted on a rod (GPS pole) with 2 meters height. Ranger controller was adjusted on the middle of the rod and connected to the GPS via data-input port using the interconnection cable. The radio modem receiver antenna was installed on the modem port of the GPS. The rover receiver setup is shown in Figure 3.10. RTK system setting was then started following the completion of the receiver setup. The setting was principally to establish the communication between the reference station and the rover receiver. This includes the process of recognizing and selecting the reference station to be used for the survey as well as checking the receiver status such as the percentage of storage memory and battery. Other than the previous mentioned, the setting also comprised RTK measuring mode properties as follow:

1. Receiver dynamics: static on occupy
2. Horizontal Root Mean Square (RMS): 0.03m
3. Vertical RMS: 0.05m

The receiver dynamics was set to static on occupy. This is suitable for land surveying which is commonly carried out by walking throughout the study area and only stopping for a few seconds to collect data on particular features. Basically, the receiver dynamics can be set to dynamic always. However, this is more suitable for RTK GPS survey when the receiver is mounted on a vehicle.

The horizontal and vertical RMS is the threshold where the accuracy may not exceed the determined value. The threshold above mostly can be achieved when the ambiguity resolution is fixed. Hence, for any result of float solution or where the accuracy lowers than the threshold, the RTK system will prompt a caution. This enables surveyor to decide whether the respective result will be accepted or it should be re-occupied again to get a better RTK solution.

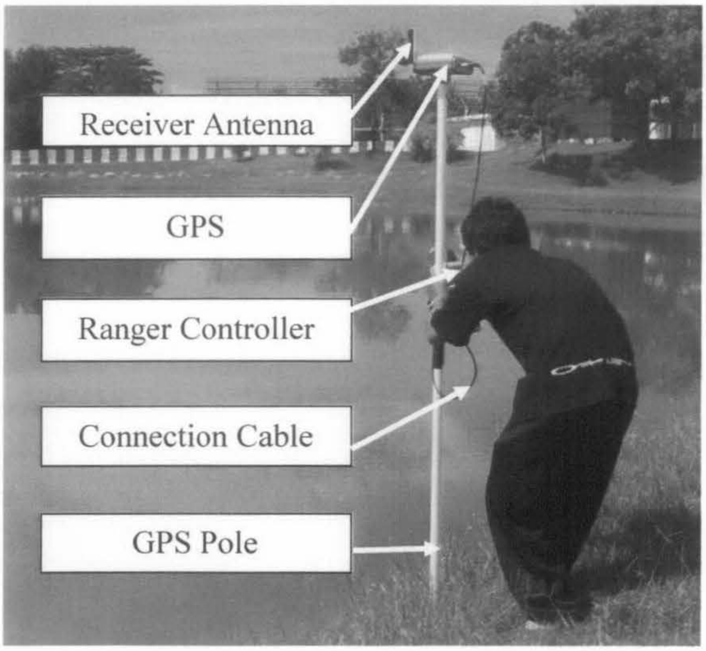


Figure 3.10 RTK GPS rover receiver setup.

3.5.1.3 Initialization check

The initialization check is aimed to monitor the RTK system for any possible errors or blunders. This is very essential since the presence of undesirable error can be investigated before the survey execution.

The procedure is basically carried out by consistently observing one point (benchmark) in the beginning of each survey. The presence of any errors can be checked by comparing the coordinates of the initialization to the known coordinates of the point. In this work, the initialization point was set on PP15 benchmark which lies approximately 20 meters on the north east side of PG01 benchmark.

3.5.1.4 Data collection of topographic features

This was conducted by walking through the entire terrain surface and collecting sampling points of existing topographic features. Initially, the features on the respective terrain were classified according to the real condition of the terrain such as road, drainage, parking lot, etc. This attribute was entered and stored on the ranger controller database. Afterward, an attribute category of terrain feature (example; parking lot) was retrieved and the survey was performed over this feature. For this kind of continuous surface, the sampling points were collected one by one, gridding with a certain density. The more flat the terrain, the fewer point sampling (less density) was carried out and vice versa.

Once the above survey completed, another terrain attribute (example; drainage) was retrieved, and the survey was continued over this feature. For this kind of selective features (drainage, road, breaklines) the sampling points were collected by tracing the features and collecting representative points to form the feature. These procedures were repeated subsequently until the whole features on the respective terrain were surveyed. This is the basic idea of composite sampling. The composite sampling was carried out at Terrain-1. The illustration of the RTK survey is given in Figure 3.11.

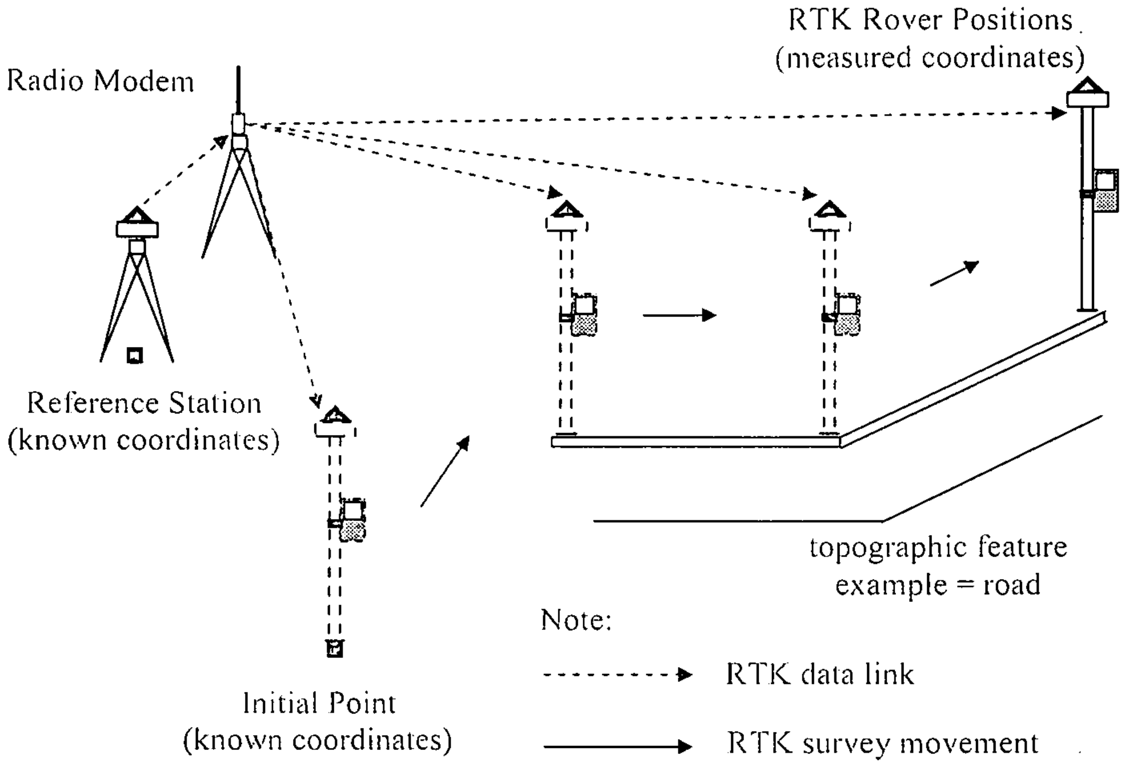


Figure 3.11 Data collection by RTK GPS.

A slightly different procedure was implemented for Terrain-2 and Terrain-3. For these terrains, a grid based point sampling was performed in spite of composite point sampling. As mentioned before, this is due to the different aims of those terrains survey design. Terrain 1 survey was designed to simulate the nature of land surveying where composite sampling is commonly applied. This is aimed to estimate the efficiency and productivity of the RTK GPS survey. Meanwhile, survey on Terrain-2 and Terrain-3 was aimed to study the effect of sky view on the quality of the RTK GPS data.

Basically, the procedure of the data collection is similar to the composite sampling. The different is that data collection was carried out over predefined survey grids. The size of each grid unit is 2.5m times 5m. Each of the grid-point was marked using temporary benchmark as shown in Figure 3.12. The use of the temporary benchmark was to ensure that both the RTK GPS and TS measured the same point so that a valid accuracy comparison can be performed. A number of 214 grid-points and 209 grid-points have been established on Terrain-2 and Terrain-3 respectively.

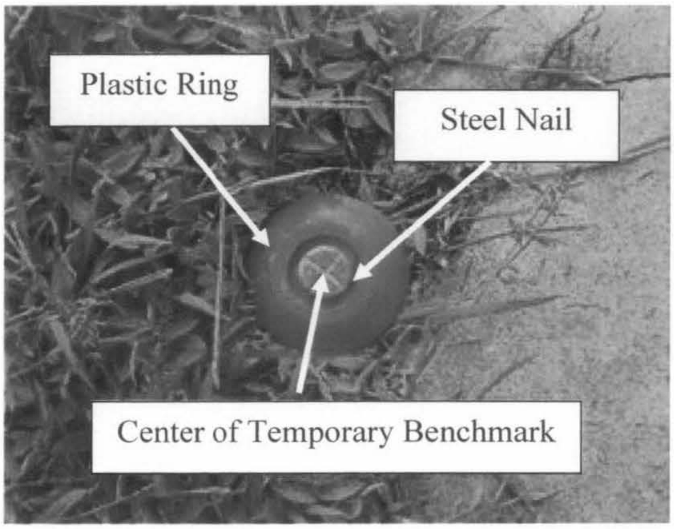


Figure 3.12 Temporary benchmark of the grid-point.

The temporary benchmark is a steel nail complemented with a high-visible plastic ring. As shown in Figure 3.12, the center of the nail is on the intersection of the cross. This enable convenience instrument centering for both of the instruments (GPS pole and TS prism pole). The high-visible plastic ring allows the nail to be easily recognized on the field.

3.5.2 DTM data collection by TS

The basic principle of DTM data collection by TS is based on polar coordinates measurement of classical survey using theodolite [48]. The different is that the angle and distance measurement on TS is done digitally. As shown in Figure 3.13, a minimum of two known benchmark is required for the survey. One benchmark is set for the occupation point (the point where we setup the TS) and the other is used as the backsight. The function of the backsight point is to set the zero horizontal angle to point the north direction (bearing=0). On this work, this was done by assigning the coordinates of both the occupation point and the back-sight point. Coding of all existing topographical features was entered in the database of the TS before the survey was started. Then, the DTM data collection was started by collecting sampling point throughout the survey area and attaching the coding of the topographic features as built on the TS database.

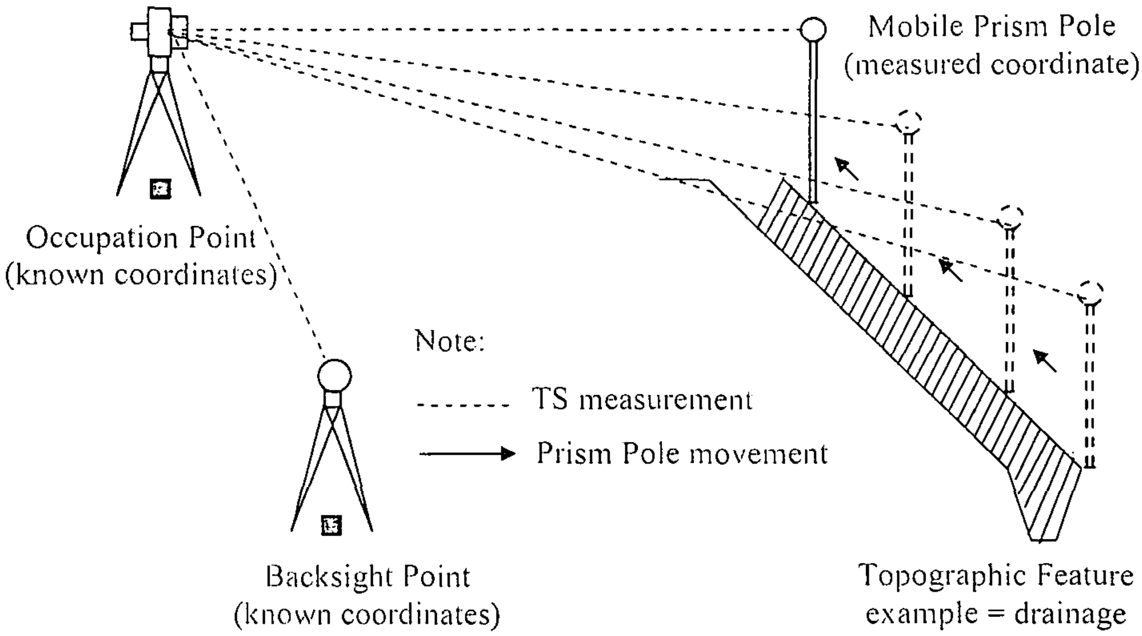


Figure 3.13 Data collection by TS.

3.6 DTM Data Processing

The DTM processing was done by using Triangulated Irregular Network (TIN). In this method, the terrain is represented by a set of vertices *v*, a set of edges *e*, and a set of triangular faces *f* [49]. The 3D co-ordinates of the raw data points are assigned to the vertices. Each edge *e* connects two vertices, and it is the intersection of exactly two faces. Each triangular face *f*, on the other hand, is bordered by exactly three edges. The edges *e* and the faces *f* describe the neighborhood relations of the original data points. The terrain is approximated by the polyhedron consisting of the triangles *f*. The surface within the triangles is assumed to be planar. The software used for the DTM processing is Arcview 3.2a^{TM}. The illustration of TIN is given in Figure 3.14.

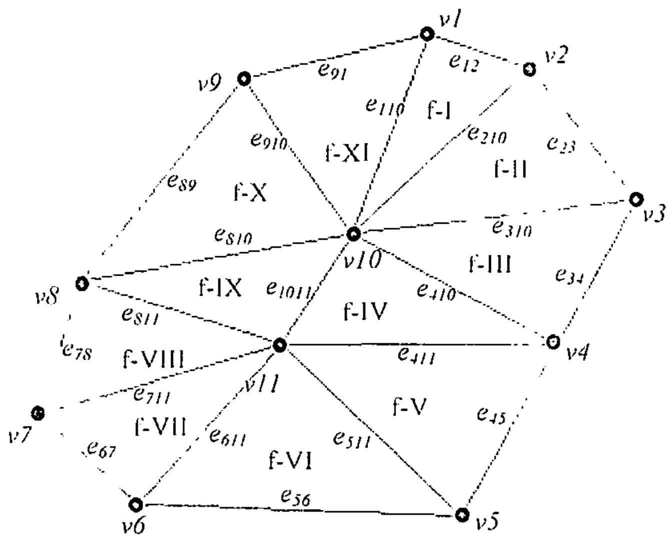


Figure 3.14 Triangulated irregular networks.

3.6.1 TIN creation

In order to create a TIN, the original data points have to be connected by edges so that triangles are formed. This was done by using Delaunay criterion, the most common optimization criterion for TIN generation [7]. In this criterion, the points are to be connected by edges to form triangles so that for each triangle no fourth point of the triangulation is within the circum-circle. The delaunay triangulation criterion yields triangles which are closest to equilateral ones. The illustration is given in Figure 3.15.

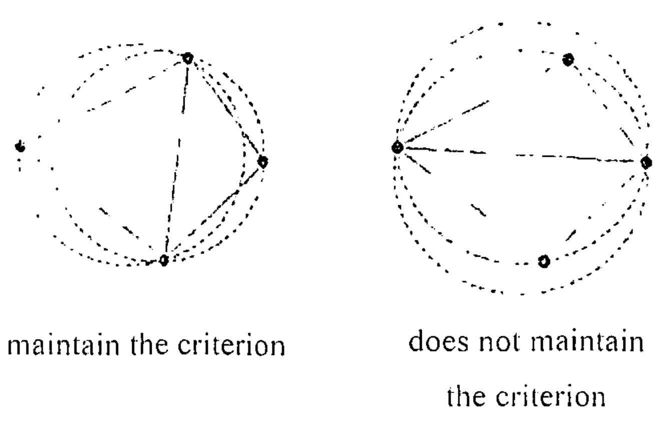


Figure 3.15 TIN creations by Delaunay criterion.

3.6.2 Breaklines creation

Breaklines, particular and specific edges of TIN elements, are defined as either hard breaklines, at which there is a physical discontinuity in slope, or soft breaklines. Soft breaklines are the edges of TIN that do not alter slope. Area boundary is an example of a soft breaklines in a TIN. While, the lines along the bottom and the tip of drainage channel are example of hard breaklines. The illustration is given in Figure 3.16.

On this work, breaklines were extracted by grouping sampling points according to their respective breaklines features such as; road, drainage, etc. These sampling points were then digitized on CAD (Computer Aided Design) software to generate breaklines. The breaklines were then inserted and compiled with the TIN.

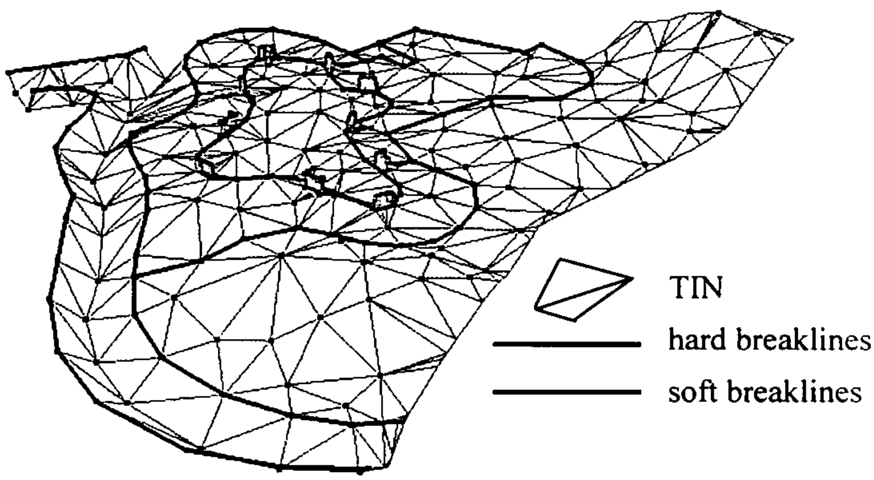


Figure 3.16 Breaklines on TIN.

3.6.3 Surface rendering

After the compilation of the TIN and the breaklines completed, terrain surface was then reconstructed. This was carried out by rendering the TIN surfaces with certain exaggeration scale for the z values, and applying color gradation on the surface [50]. This is intended to help visual associative recognition of the DTM surface such as; height differences, discontinuities, height values, etc.

3.6.4 Volume computation

The merit of using TIN is the ability to represent the topographic information at a both small and large scale of resolution. Furthermore, by using TIN, it is also easy to define the volume of the DTM.

All volume computations in the TIN programs are based on simple mathematical formula of triangular prism [51]. The volume is determined by the multiplication of the medial high with the area. The formula is as follow;

$$h_{mi} = \frac{h_{i1} + h_{i2} + h_{i3}}{3} \tag{3.2}$$

$$V_i = F_i * h_{mi} \tag{3.3}$$

$$V = \sum_{i=1}^{n} V_i = \sum_{i=1}^{n} F_i * h_{mi} \tag{3.4}$$

where;

i	: name of one triangle
n	: number of all triangles
h_{i1}, h_{i2}, h_{i3}	: height of each vertex of one triangle
h_{mi}	: medial height of one triangle
V	: volume of the object
V_i	: volume of one triangle
F_i	: area of one triangle

In this method, the volume is computed above a certain reference plane. In this work, the reference plane was defined by referring the lowest height value of the grid-point.

3.7 Quality Measure of DTM

One of the consequences of using DTM, especially in high accuracy applications, is the need to characterize the DTM quality. This is particularly a relevant issue in civil engineering where, beside the technical implications, a lack quality in the DTM can lead to important economic deviations during project execution. The quality control presented in this work is based on the common parameters used in civil engineering to determine the quality of a DTM [5], that are:

i. The height error analysis
ii. The volumetric error analysis

The volumetric accuracy analysis is a simple yet useful method for DTM quality control. This is based on the idea that DTM quality can be analyzed by the ability to estimate soil volumes. This criterion was introduced given the economic importance that the control of volume has in civil engineering applications. The consequence of this method is the need of a reference model to be used for volume comparison. This method allows a global analysis of the model but it does not allow us to determine the presence of systematic errors that, particularly with the height value have a great impact in the quality of the DTM. Hence, to avoid this problem the height error analysis was introduced to complement the volumetric error analysis.

1.7.1. The height error analysis

The height error analysis has several advantages:

i. It allows the characterization of height errors of the model
ii. It serves as control over the volume estimation method
iii. It needs only a set of strategic points to have a control over the models

In this work, the height error analysis was carried out on all of the study areas. For Terrain-1, this was carried out over two profiles across the area. For Terrain-2 and Terrrain-3, it was performed over the grid-points. The analysis was conducted by analyzing the discrepancy between the value given by RTK GPS and total station survey. The statistical measures used for this are:

$$\mathrm{E}_{m} = \frac{\sum e_i}{u} \tag{3.5}$$

$$\mathrm{E}_{ma} = \frac{\sum |e_i|}{u} \tag{3.6}$$

where:

E_m = mean error
E_{ma} = absolute mean error
e_i = individual error of one point
u = total number of points.

The average error is a good indicator of the randomness of the errors to test the existence of important systematic errors in the height value [5]. Hence, the absolute mean error is the most suitable indicator of DTM accuracy. The fact that it is expressed in absolute terms has the advantage that errors with different signs will not cancel each other which allow a more rigorous characterization of errors.

3.7.2 The volumetric error analysis

The volumetric error analysis was performed by analyzing the difference of computed volume between the DTM generated from RTK GPS compared to the respective DTM based from TS data. Here, the latter was used as the reference model. This is due to some theoretical and practical reasons. Firstly, total station accuracy (0.3cm ± 3ppm) is relatively better than RTK GPS that is 1cm ± 1ppm for horizontal positioning and 1.5cm ± 1ppm for vertical positioning. Secondly, it is free from errors contributed by surrounding or sky view whereas is an important parameter in RTK GPS survey. This is due to the fact that the quality of RTK GPS data normally depends on the sky view and the condition of the survey area. Hence, it is interesting to investigate of how far the sky view affects the accuracy of RTK GPS data and its influence to the generated DTM. Beside, it is also important to approximate the workable and usable sky view for RTK GPS survey. These are specifically correlated with the efficiency and productivity as well as the accuracy of the RTK GPS. Practically, total station survey is the conventional technique that has been used for years. Hence, the RTK GPS, which is a new method in term of DTM data collection, should be tested against the conventional method that is Total Station.

The volumetric accuracy analysis was performed based on DTMs of Terrain-2 and Terrain-3. This is intended to have a valid analysis since both of the DTMs are based on grid based sampling which uses exact grid-point. The volumetric error analysis is unlikely to be performed on DTM of Terrain-1 which is based on composite sampling. This is due to the fact that the RTK GPS and TS data gained from this sampling are different in term of spatial position since no exact same point can be used for the analysis. Hence, the DTM generated from RTK GPS survey data is totally a different model compared to the one generated from TS survey data.

3.8 Experiment Workflow

This work is carried out in five steps; preparations, data collection, data processing, quality measure as well as efficiency-productivity estimation, and assessment. The workflow is illustrated in Figure 3.17.

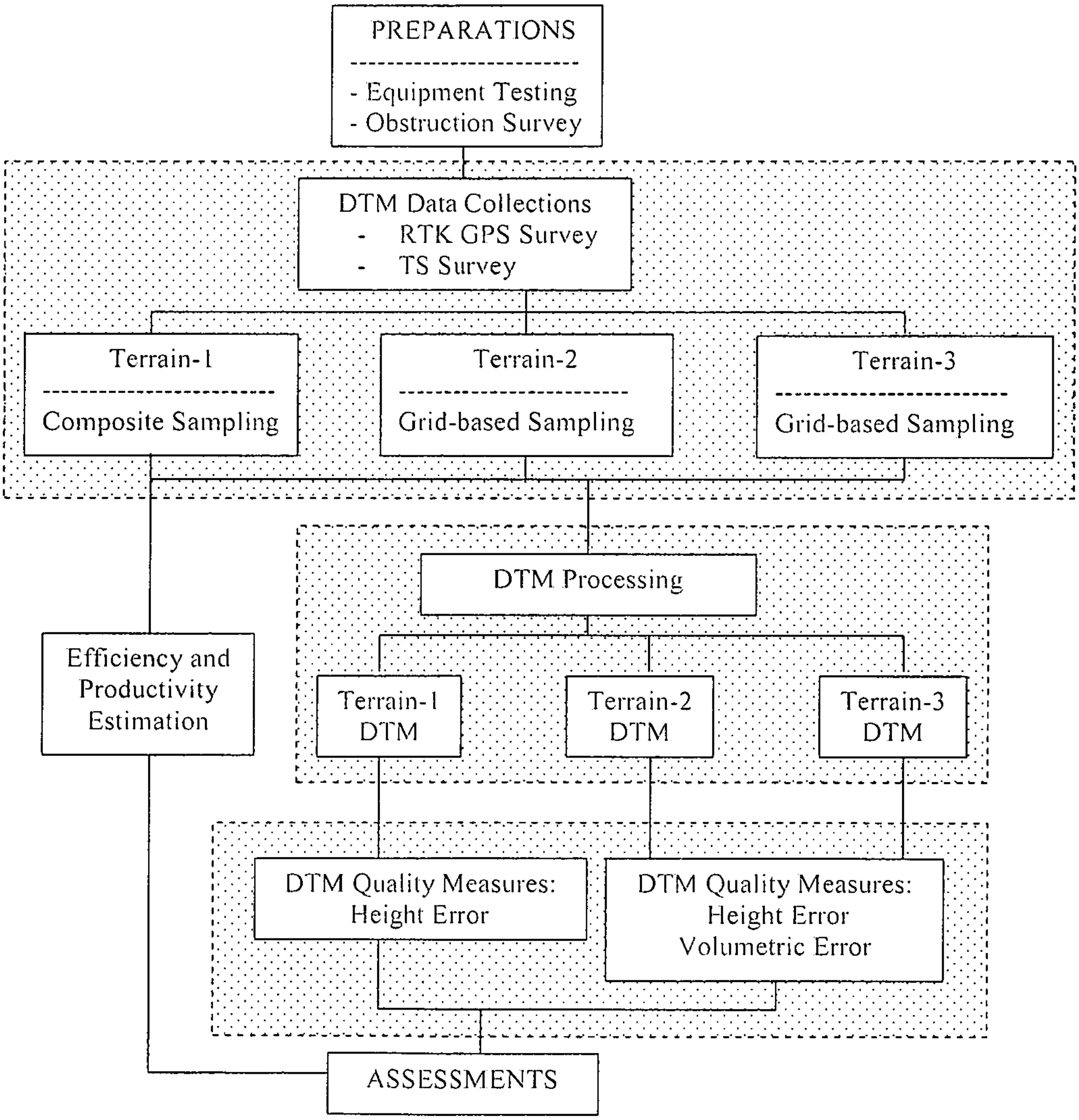


Figure 3.17 Experiment workflow.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter shows results of experiment described in the previous chapter. The results consist of; equipments testing, obstruction survey, DTM data collection, data processing, productivity and efficiency estimation, and DTM quality measure.

4.1 Equipment Testing

The RTK GPS equipment has been tested. The testing duration was approximately six hours of continuous RTK observation, with 15 seconds data recording interval. The observation successfully collected 1345 of RTK points. The result is shown in Figure 4.1 and Figure 4.2.

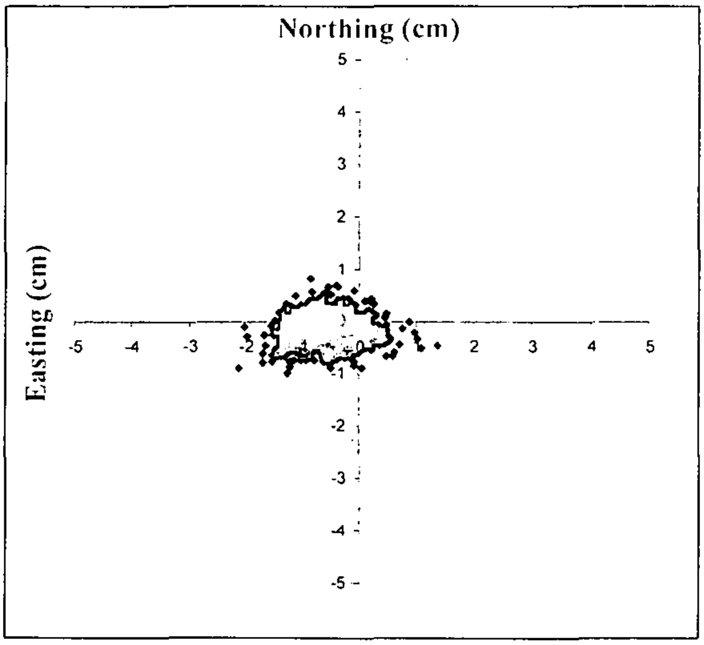


Figure 4.1 Scatter plot of horizontal drift.

As shown in Figure 4.1, the maximum value of horizontal position drift is 2.11cm for easting and 0.84cm for northing with average drift of 1.17cm and 0.48cm respectively.

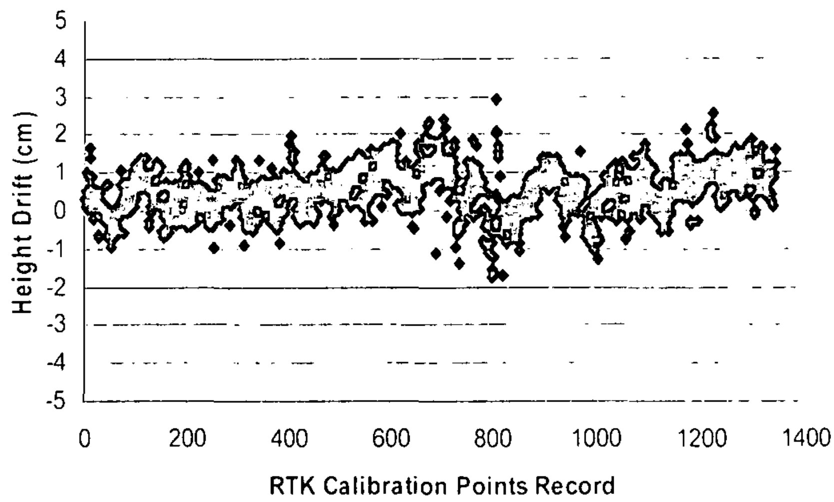


Figure 4.2 Scatter plot of height drift.

As shown in Figure 4.2, most of the drifts values are lower than 2.5cm, except for record number 805 and 1219 that is 2.92cm and 2.53cm. Overall result shows that the height drift is higher than the horizontal position drift. This drift signs the well accepted facts that the height accuracy of GPS is lower than the horizontal accuracy. The statistic of the test is shown in Table 4.1.

Table 4.1 Statistic of the RTK GPS testing.

Drift	Minimum (cm)	Maximum (cm)	Average (cm)	RMS (cm)
Easting	0.11	2.11	1.17	0.88
Northing	0.10	0.84	0.48	0.36
Height	0.15	2.92	1.21	0.97

Referring to the test result as shown in the Table 4.1, it is evident that the accuracy of the RTK GPS is very good and fitting the accuracy stated by the manufacturer where horizontal accuracy is 1cm±1ppm and vertical accuracy is 1.5cm±1ppm. This means that the RTK GPS used in this work is in a good condition and capable of giving appropriate accuracy for the experiment.

The Total Station used on this experiment has also been tested. The testing was carried out by measuring several distances between known pillars, and comparing the result gained by Total Station to the known distance between pillars. The result is given in Table 4.2.

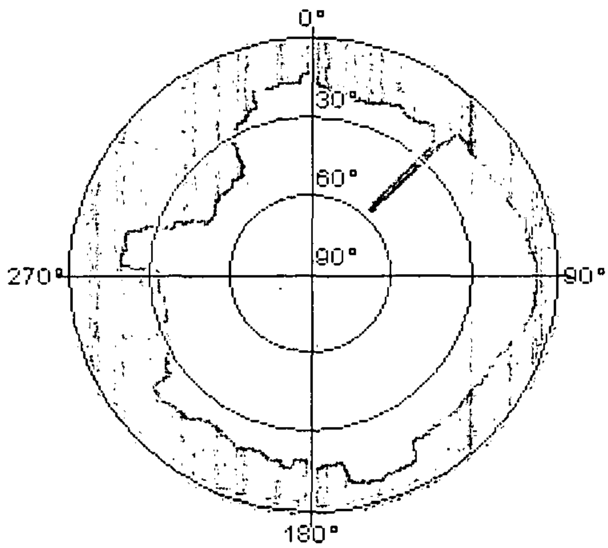
Table 4.2 Statistic of TS testing.

Pillars	Known Distance (m)	Total Station (m)	Differences (cm)
BM1-BM2	5.004	5.005	0.1
BM1-BM3	10.002	10.001	0.1
BM1-BM4	49.002	49.002	0.0
BM1-BM6	125.000	125.002	0.2
BM1-BM8	201.002	201.004	0.2
BM1-BM10	300.008	300.011	0.3

According to Table 4.2, it can be seen that the difference between the TS result and the known distance, for BM1-BM2 and BM1-BM3 is only 0.1cm. While, for the BM1-BM4, BM1-BM6, BM1-BM8, and BM1-BM10 are 0cm, 0.2cm, 0.3cm, and 0.3cm respectively. The accuracy of the TS as stated by the manufacturer is 0.3cm ± 3ppm. The above testing shows that the result is consistent with the stated accuracy. It is evident that the Total Station is still in good condition and capable of giving reliable data for the experiment.

4.2 Obstruction Survey

The obstruction survey was carried out by using TS over set of strategic spots on each study area to estimate the average sky view value. PG01 benchmark which was used for the base station of all survey has an approximately 75% sky view, as shown in Figure 4.3.



☐ Obstruction : 25%
☐ Sky view : 75%

Figure 4.3 Obstruction diagram of PG01 base station.

Hence, technically, the value of sky view for all rovers' position throughout the study area was automatically equal or less than 75%. This is due to the fact that the rover's 3D coordinates of the RTK measurement is differentiated from the base station. Therefore, no matter how better the sky view of the rover points, the differentiation process were only performed based on satellites tracked on the base station , where indirectly depends on the sky view of the base station. Therefore, the obstruction surveys on the study area were merely carried out over several parts of the area where the sky view is approximately equal or worse than the base station.

Terrain-1 is a complex terrain with various skies of views ranging from 50% to 75%. The obstructions on this terrain are typically contributed by buildings and various vegetations throughout the survey area. The illustration of Terrain-1 and its sky view are given in Figure 4.4.

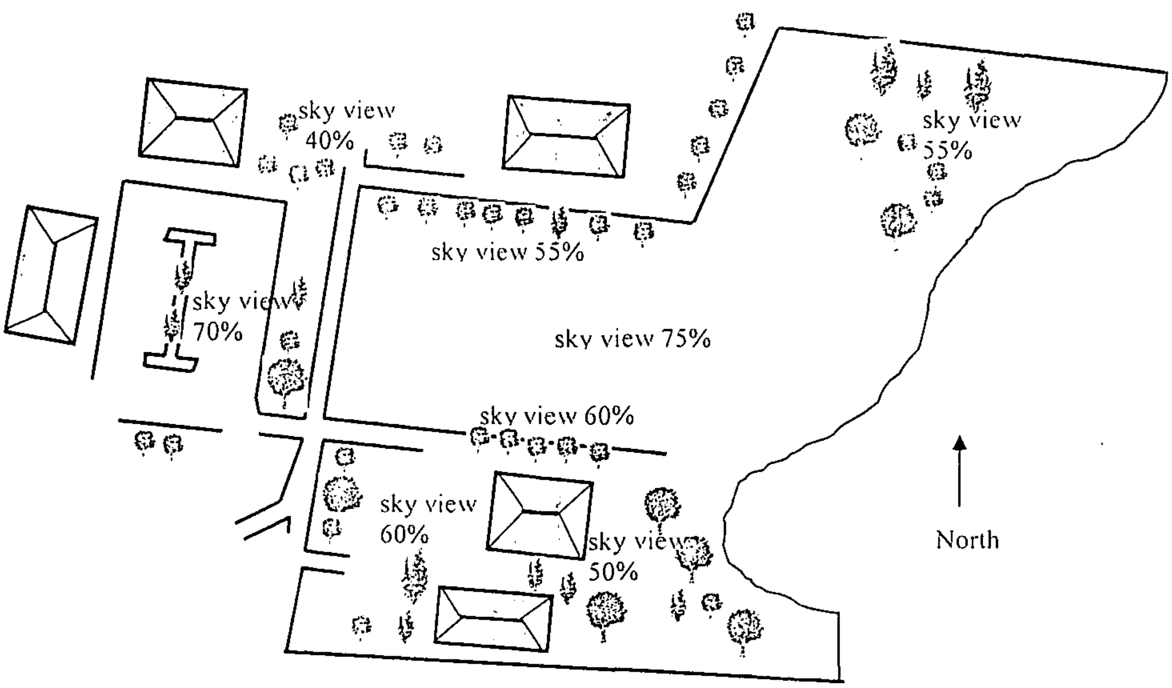


Figure 4.4 Sky view illustration of Terrain-1

Terrain-2 is a relatively open area. The obstruction is mostly contributed by vegetations on the northern and western side of the area edges. The average sky view on the open area is 75%, while for the edge of the area is 55%. The total average sky view is approximately 68%. The illustration of the area is given in Figure 4.5.

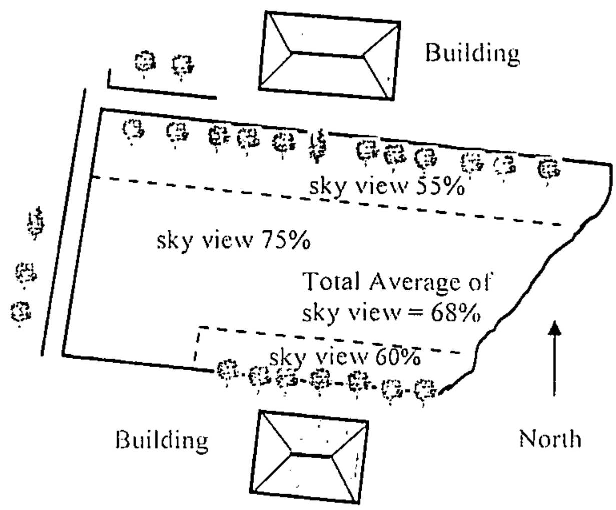


Figure 4.5 Sky view illustration of Terrain-2

Terrain-3 is significantly different from the previous two terrains in term of obstruction level. It has much less total average sky view of approximately 59%. This is due to the various vegetations that cover almost half of the entire area. The illustration of the area is given in Figure 4.6. The average sky view on the open area is 62%. The trees along the corridor of the road on the western side affect the sky view to drop a bit to 59% for the respective area. The sky view decrease until 55% for the highlighted area (upper right side of the illustration) due to the coverage of pine trees over the area. While, on the lower right side, it decreases until 49% due to the coverage of dense various vegetations.

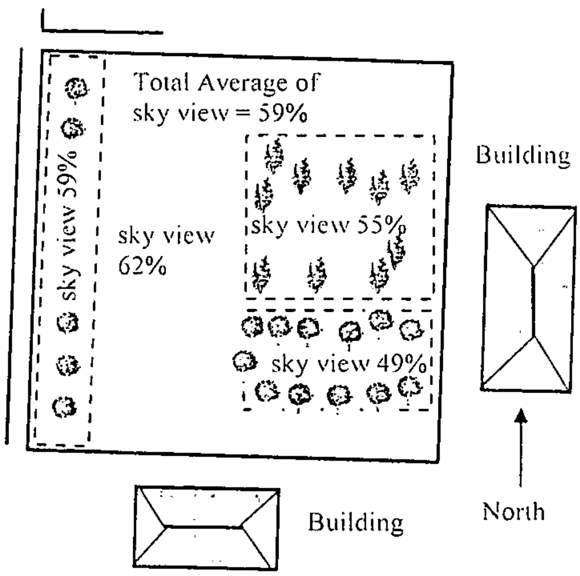


Figure 4.6 Sky view illustration of Terrain-3

4.3 DTM Data Collection

The DTM data collection was conducted by two techniques, that is composite sampling and grid based sampling.

4.3.1 Composite sampling

The DTM data collection by using composite sampling was performed on Terrain-1. This was intended to adapt the nature of land surveying of where total station is commonly employed. This comprises both selective sampling and grid-based sampling. Generally, abrupt or sudden changes (structural features on the terrain such as drainages, road-edge, retaining wall, etc) are sampled selectively. Meanwhile, plain area, hollow, and other continues surfaces are done by grid-based sampling.

A pre-survey was conducted throughout Terrain-1 to classify the existing topographic features. This classification is the basis of the coding and the numbering as required by the RTK data storage system. The classification is given in Table 4.3 below.

Table 4.3 Classification of existing topographic features.

Topographic Feature	Code	Point Number/ID
Breaklines	BRKL	1000 - 1999
Building	BLDG	2000 - 2999
Drainage	DRAN	3000 - 3999
Parking Lot	PRKL	4000 - 4999
Road	ROAD	5000 - 5999
Topography	TOPO	6000 - 6999

This classification is very essential since the coding and the numbering of the data collection is based on this. The coding was used during the data collection to address the 3D coordinates of the sampling point to its respective classification of topographic feature. The numbering is very important since each of the point number has to be recorded with a unique point ID. Any redundancy on the numbering can lead the data to be overwritten and lost. The range of the point number can be adjusted depends on the size of the area or the estimation of the amount of the points. Based on the classification above, the grid-based point sampling was employed for parking lot and topography and selective sampling was employed for the rest of the features. The coding and the numbering were then applied and stored on the ranger controller database.

The RTK GPS rover receiver setting used during the data collection were; 10° cut-off angles, minimum number of satellites in view is 5, and maximum Dilution of Precision (DOP) is 6. This basic setting was aimed to ease the survey execution and in the same time also to maintain the quality of the data. The RTK GPS setting was also adjusted so that it can provide a real time alert for the presence of any float RTK solution, or when the solution exceeds the RMS threshold of the 3D position error (horizontal RMS = 3cm, vertical RMS = 5cm). This was intended to enable re-occupation for sample points with RTK solutions accuracy lower than the threshold.

The rover receiver was mounted on a GPS Pole. It was equipped with level bubble which enables the surveyor to maintain the pole vertically during the sampling point occupation. The DTM data collection was carried out by collecting sampling points of the existing topographic features throughout survey area point by point. This was to ensure representative data collection of all existing topographic features.

Result of the survey execution shows that fix RTK solutions can be achieved relatively easy on the open area (sky view 75%). For this, 7-8 satellites were tracked during the survey. It took only 1-3 seconds to do each of the occupation. While, float RTK solution were mostly occurred on sampling points under vegetations or when close to buildings (sky view below 60%). Fewer available satellites in view were recognized (5-7 satellites). The precision of the entire fix solutions were ranging from 0.6cm to 1cm for horizontal position, and 0.6 to 1.5cm for the height. While, for the float solutions, it were mostly ranging from 0.9cm to 1.6cm for the horizontal position, and 1cm to 2cm for the height.

There were a few cases of float RTK solution where the precision exceeded the predefined threshold. This was occurred particularly on several sampling points under dense vegetation (sky view 50%-55%). For this, the number of the available satellites in view were dropped (4-6 satellites). Therefore, to achieve better RTK solutions, re-occupations were carried out on the respective sampling points. Each of the re-occupation was conducted by moving to an open area and re-initialized the RTK system. Once the re-initialization succeeded, the respective sampling points were re-surveyed. The successful of the re-initialization were signed by the changing of RTK solution, from float solution to fix solution. Generally, it took 1-2 minutes to complete the re-initialization. By doing the above technique, better RTK solutions can be acquired.

4.3.2 Grid-based sampling

It was carried out by collecting 3D position over a regular grid sized 2.5m times 5m. Each of the grid-point was marked using temporary benchmark. This was intended to ensure that both total station and RTK GPS survey observed exactly on the same point. Firstly, total station survey over the grid-points was carried out, then, RTK GPS survey was performed through the respective grid-points.

Data collection on Terrain-2 was quiet straight forward since most of the area is an open area (sky view 75%). RTK fix position can be attained easily where the available satellite in view was mostly at 6 or 8 satellites. A low number of DOP (3-5) also contributed to the ease of achieving those fix RTK solutions. There were only a few cases of float solution for some grid-points occupation on the northern part of the area where it is covered by trees (sky view 55%). The precision of most fix RTK solutions were ranging from 0.6cm to 1.2cm for horizontal position, and 0.8 to 1.5cm for the height. While, for the float solutions, it were ranging from 0.9cm to 1.5cm for the horizontal position, and 0.9cm to 2cm for the height.

Considering the above results, it can be seen that these three factors, that are; good sky view , adequate number of satellites in view, and low value of DOP ease the achievement of fix RTK solution, and at the same time, speed up the survey execution since no re-occupations needed.

Different from the previous survey, data collection on Terrain-3 is relatively slower and less convenience. This is due to the condition of the terrain where nearly half of the area is covered with various vegetations. Fix solution still can be collected relatively easy on the open area (highlighted by blue). But unlike the previous survey on Terrain-2, several float solutions occurred on the open area, particularly on grid-points which was close to the obstructed area. The illustration of RTK solutions are shown in Figure 4.7.

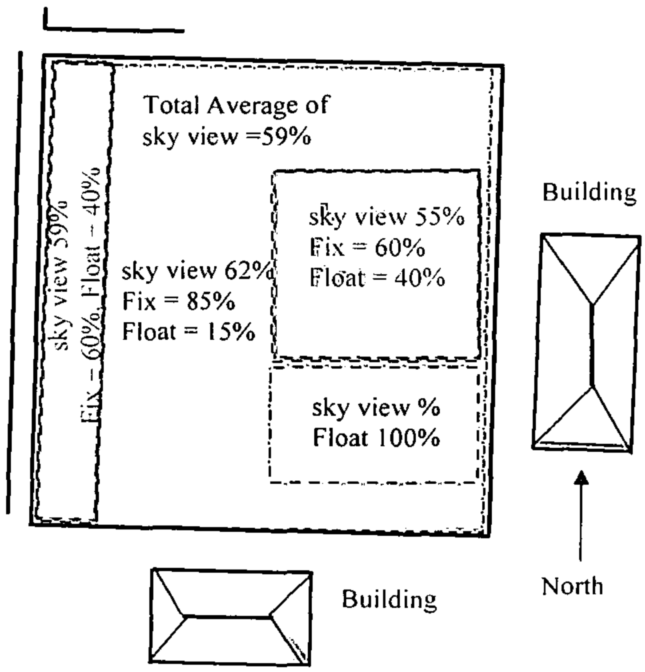


Figure 4.7 RTK solutions on Terrain-3

Most of the fix solutions have approximately the same precision as gained on the previous survey. While, float solutions have a bit lower precision (1.2cm to 2.5cm for horizontal position, and 2cm to 4cm for the height). As shown in Figure 4.7, for the area with sky view between 50% and 60% (highlighted by green), the RTK float solutions were almost one third of the total sampled points. While, the rest two third of the solutions were fix solutions. This was due to the less available satellite in view of 5 to 6 satellites. Amongst those float solutions; there were few cases where re-occupations were performed to get a better solution. This was particularly done for float solutions which exceeded the predefined RMS threshold. As it happened before, it took 1-2 minutes to perform the re-occupation. While, for area with average sky view below 50% (highlighted by yellow), all RTK solutions were float. The available satellite was at 4 to 5 satellites. Re-occupation were performed over nearly three fourth of the total grid-points. Unlike the previous re-occupation, it took much longer time to perform the occupation (2-4 minutes). These re-occupations effected the data collection to be much slower and less convenience.

4.4 DTM Data Processing

The DTM processing was done by using Triangular Irregular Network (TIN) using Arcview 3.2a™ software. Raw data of the sampling points was downloaded from the internal storage of the ranger controller to computer using Microsoft Active Sync™ software. The downloaded file was a tab delimited text file consisting 3D coordinates of the sampling points. Each of the categories was separated by a tab. This raw data were then edited by giving a header on the first line of the text file as shown in Figure 4.8. The data are available in Appendix C, however, due to the large amount of data (2269 points), only a part of the data was attached.

```
1098	484874.734	718733.298	24.823	BRKL
1099	484874.577	718754.135	22.976	BRKL
1100	484874.747	718754.113	23.142	BRKL
1101	484874.667	718780.582	22.731	BRKL
1102	484874.822	718780.640	22.956	BRKL
5045	484873.033	718780.354	22.662	ROAD
5046	484872.985	718774.451	22.687	ROAD
5047	484872.920	718766.613	22.799	ROAD
```

Point Number	Northing	Easting	Height	Code
1098	484874.734	718733.298	24.823	BRKL
1099	484874.577	718754.135	22.976	BRKL
1100	484874.747	718754.113	23.142	BRKL
1101	484874.667	718780.582	22.731	BRKL
1102	484874.822	718780.640	22.956	BRKL
5045	484873.033	718780.354	22.662	ROAD
5046	484872.985	718774.451	22.687	ROAD
5047	484872.920	718766.613	22.799	ROAD

Figure 4.8 DTM raw data.

The header is important especially during the initial processing of the TIN where software requires verification of the field X, Y, Z and code. All sampling points were used for the TIN creation. Sampling point coded as breaklines and other continue line features that considered and used as breaklines (drainage and road) were separated. This breaklines were then digitized to be compiled with the TIN. The digitization were done either by manual on-screen digitization or automatic script command by using AutoCAD™ software. Script commands were used to construct simple breaklines connecting set of successive points. Manual line tracings were carried out to construct breaklines of complicated object such as drainage control vessel.

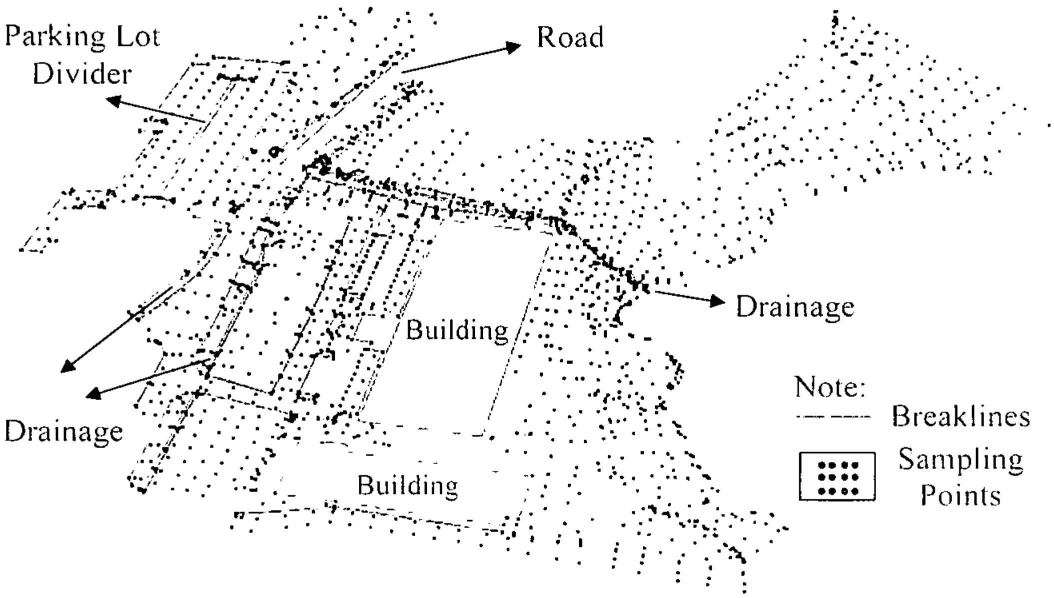


Figure 4.9 Breaklines.

As shown in Figure 4.9, the breaklines were used to reconstruct abrupt changes or to force the TIN to follow the trend of the breakline. As an example, for the drainage breaklines, the edges of the TIN on the surrounding of the respective breakline were forced to follow the bottom and the tip of the drainage channel. The same command goes for the road breaklines where the edges of the TIN were obliged to follow the bottom and the tip of the pavement on the edge of the road.

Unlike the drainage and road breaklines, breaklines of building were used to force the TIN edges on the surrounding to reconstruct plane area inside the breaklines.

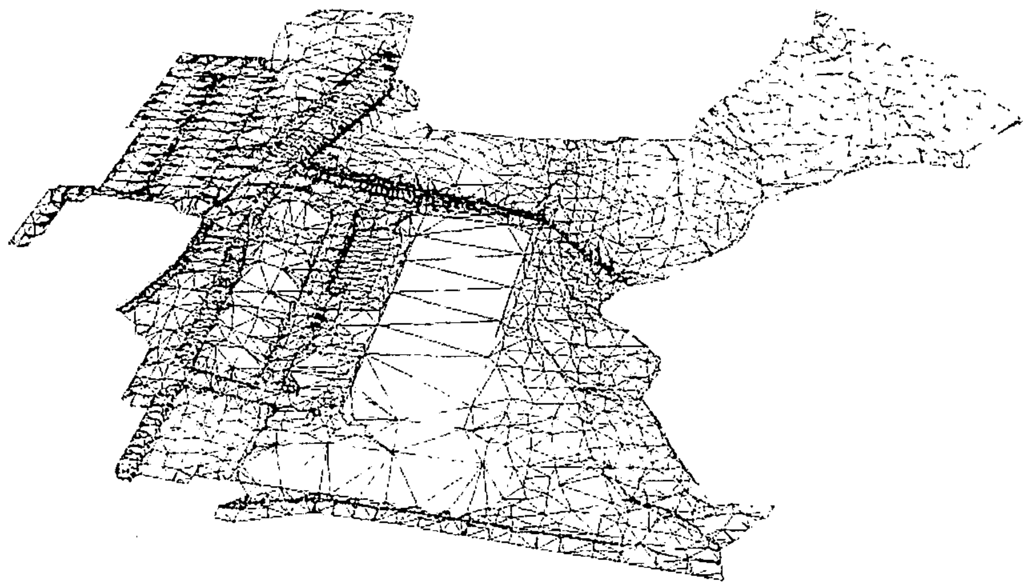


Figure 4.10 TIN and breaklines.

Figure 4.10 shows the TIN which was already complemented with breaklines. Basically, the breaklines forced the edges on the surrounding TIN by splitting the existing triangle faces into smaller triangle faces. Figure 4.11 gives a screenshot of a closer look of a portion of the TIN with its breaklines.

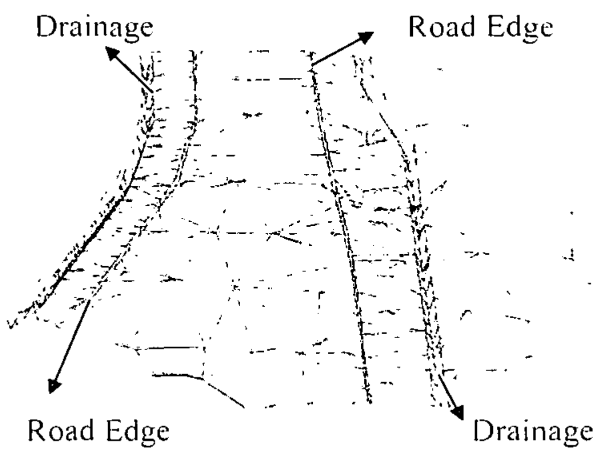


Figure 4.11 TIN and breaklines

These new smaller triangle faces were interpolated using the same TIN algorithm (Delaunay Criterion) by referring to the position and the height of the breaklines. This is how the TIN reconstruct sudden changes and truly plane/flat area by using information from breaklines.

The surface of the DTM was reconstructed by rendering the TIN surface with certain exaggeration scale for the height value. This was to have an ideal visualization of DTM where the details of the surface can be easily recognized. The exaggeration scale is the ratio between the horizontal scale and the vertical scale. Figure 4.12 gives the visualization of the DTM by using 2.0 exaggeration scales. By using this value, the detail of the DTM surface can be viewed nicely. Giving too low number of exaggeration scales (1-1.5) will give an impression that the terrain is flat. On the other hand, giving too high value (3 and above) will affect the DTM to look like a hilly terrain.

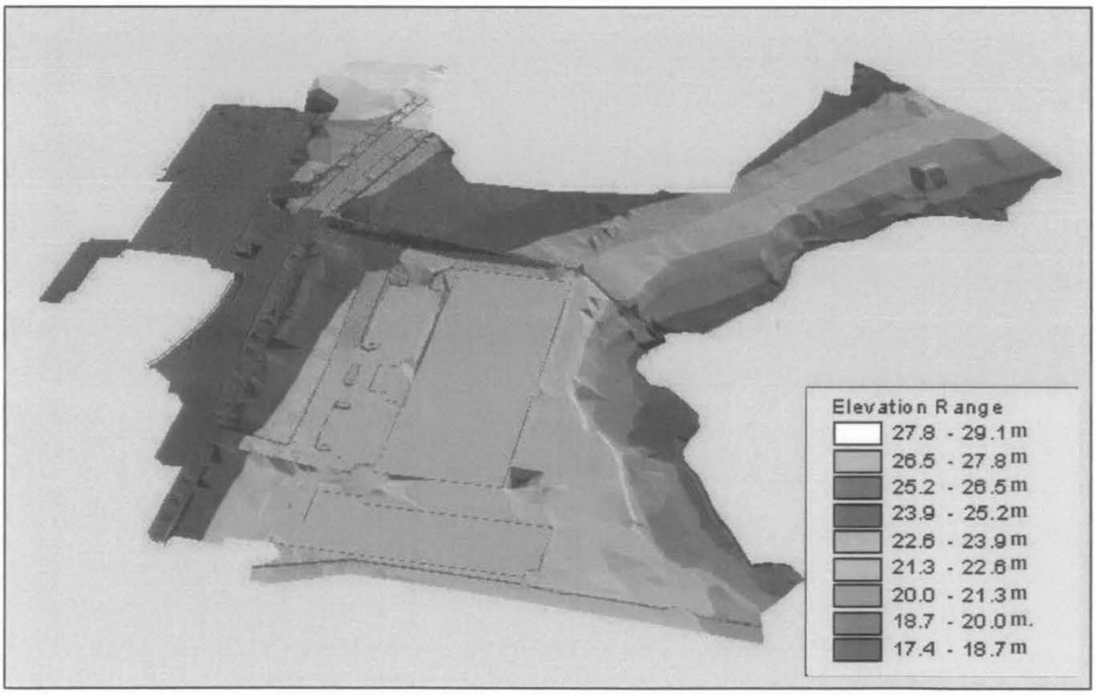


Figure 4.12 DTM surface

The color gradation and its legend help associative recognition of the height of the surface throughout the DTM.

As defined in chapter two, DTM represents the bare earth surface devoid of landscape features such as; buildings, trees, etc. Nevertheless, for some applications such as in landscape modeling, it is frequently important to represent building on the DTM surface. Therefore, in this work, two buildings on the survey area were also represented. This was done by using the breaklines information. Having the breaklines of the building connecting edges of the building, a simple representation of the buildings can be visualized by extruding the breaklines with certain value according to the actual height of the building.

DTM could also represent the surface of water-bodies. As an example, the pond located on the eastern side of the study area was visualized. This was basically done by creating horizontal flat surface according to the height value of the water surface. For this, it referred to the height of the breaklines along the bank of the pond. Figure 4.13 gives the representation of the DTM complemented by buildings and pond surface.

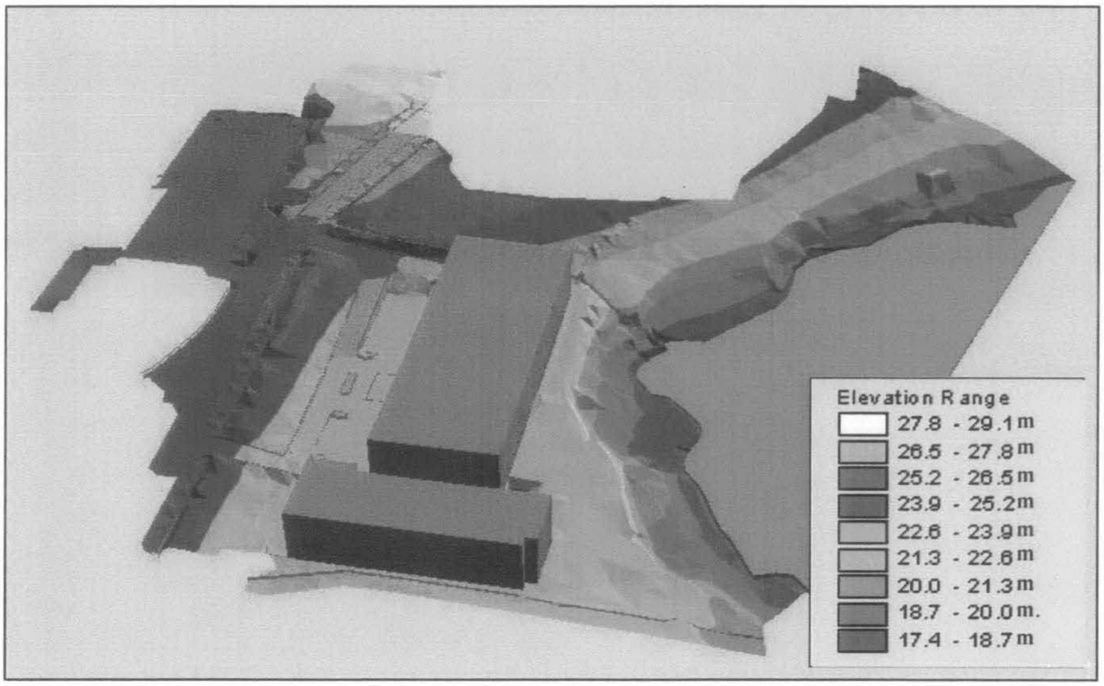


Figure 4.13 DTM complemented by buildings and pond surface

The DTM generated on this work is a high resolution DTM. A high resolution DTM should capable of presenting terrain in high fidelity. This means that the DTM should resemble the actual terrain surface as close as possible. Generally, the resemblance between the DTM and the actual terrain depends on the density, selection, and distribution of sampling points as well as the DTM processing approach used for the modeling.

Figures 4.14 and 4.15 give a screenshot of the generated DTM and the picture of a parking lot divider which has an approximately 20cm of vertical thickness. It can be seen that the generated DTM is very similar to the actual feature. The parking lot which is a relatively flat terrain can be finely represented as well.

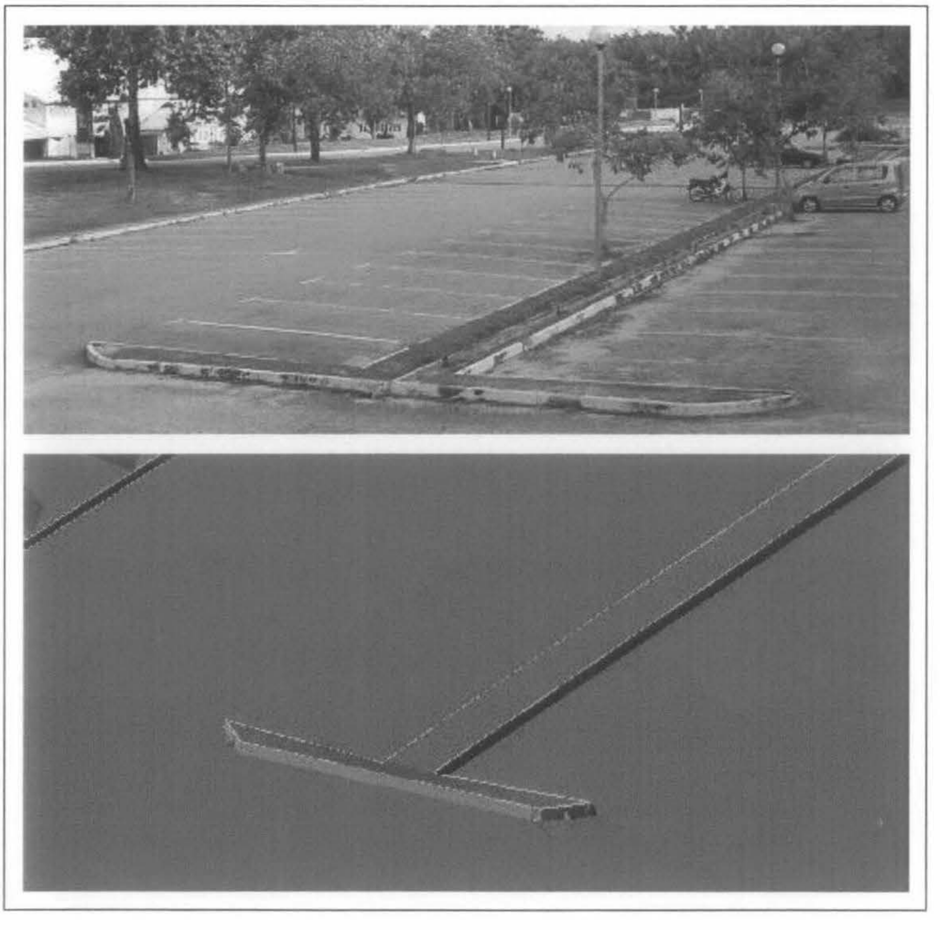


Figure 4.14 Parking lot on actual terrain and the generated DTM

Figure 4.15 Divider of parking lot on actual terrain and the generated DTM

Slight differences between the actual and the model were noticed on the rounded corners of the divider. This was basically due to generalization during the data collection where sampling points were only taken on the lower and upper edges of the divider. Small ditch on the middle of the divider was ignored and no sampling points collected. That is why the respective feature is not represented on the DTM.

The resemblance between the actual divider and the model shows that the object reconstruction was quiet easy. It can be noticed that the breaklines taken along the bottom and the tip of the divider can force the TINs on the surrounding to follow its trend. From the point of view of the input data accuracy, it can be pointed out that the input data given by RTK GPS survey over this area (sky view 70%) are reliable.

Figure 4.16 Island markers on actual terrain and the generated DTM

Figure 4.16 shows another screenshot of the DTM and the picture of respective real island marker which has vertical thickness of about 25cm. It can be seen that the generated DTM gives a close likeness to the actual object. The fact that the sky view on the respective area was a bit lower (60%) did not give a significant impact on the quality of the input data.

The above two examples were taken from parts of the DTM which presents regular features over relatively flat terrains. Figure 4.17 gives an example of regular features over an irregular curvy terrain. It can be seen that the breaklines along the drainage channel successfully forced the TIN to represents the respective feature on the DTM. However, an apparent difference can be recognized between the actual curvy terrain on the surrounding of the drainage and the respective surface on the DTM. This is particularly the characteristic of TIN approach where the reconstruction of curvy terrain highly depends on the selection, distribution and density of the sampling points. The more density and the more representative selection of sampling point distribution, the better curvy surface can be represented on the DTM. The point density of the DTM shown in Figure 4.17 is approximately 4 points per m^2. Higher point density is required to reconstruct the respective area into a curvier surface.

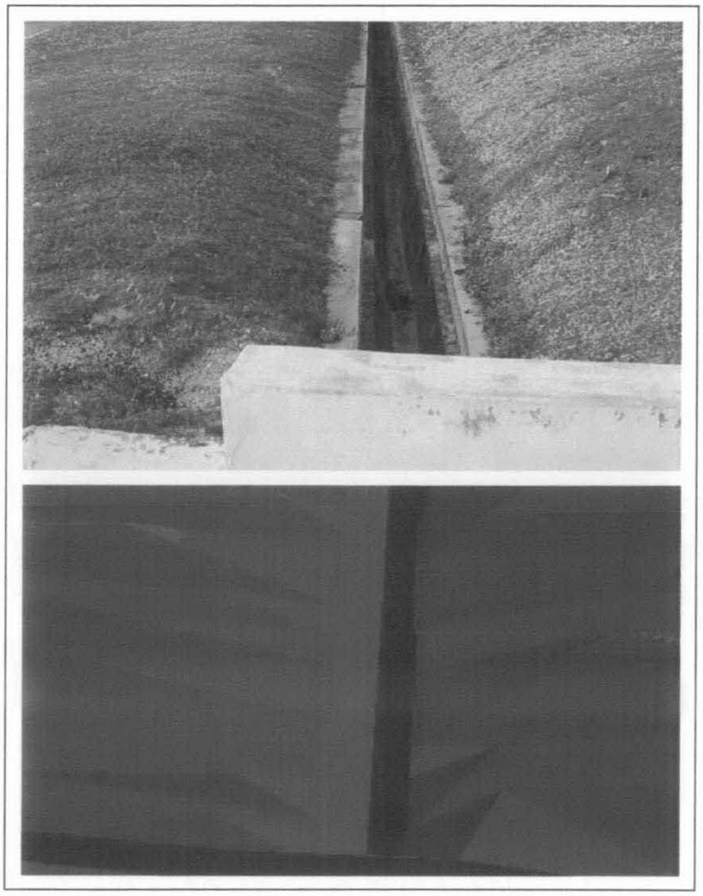


Figure 4.17 Drainage channels on actual terrain and the generated DTM

From the results obtained, it can be concluded that DTM generated from TIN has good flexibility on reconstructing structural features either for abrupt changes or continuous flat terrains, by incorporating breaklines information. Features with regular shape are easier to reconstruct than curvy terrain. To create a smooth surface over a curvy terrain, higher sampling point density is required.

Few outliers were found on the DTM. This was particularly presence on portions of the DTM where the sampling points were collected under average sky view of 50%. Figure 4.18 shows one of the outliers where a continuous surface where oscillated by two points with a noticeable errors, particularly on the height values. The errors of the respective points were in decimeter level (15-19cm). This was done by comparing the height of the continue surfaces and the height of those two points. Worse error was recognized on part of the DTM where the average sky view is 40%. For this, the error reached 40cm.

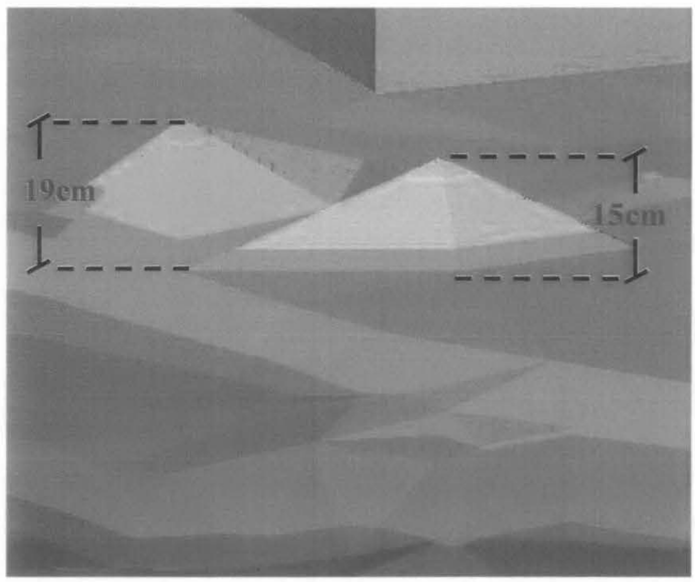


Figure 4.18 Errors on the DTM

From the above facts, it can be pointed out that using RTK GPS for area with average sky view below 50% will lead to a risk of having outliers on the data, especially for the height. Therefore, the use of RTK GPS for DTM data acquisition is recommended for area with sky view above 50%. More details on this are discussed on the section 4.6 of this chapter (DTM quality measure).

Besides intervisibility, prism targeting was another factor why the TS survey was slower than RTK GPS survey. Generally, for each measurement, it took sometime for the TS operator to shoot the prism and to center the cross hair of the TS precisely on the center of the prism.

The DTM data collection on Terrain-2 can also be used as a comparison. Result of experiment shows that it took only about 1.5 hour to complete the RTK GPS survey over 214 grid points on an area size of approximately 6400m^2, while the TS survey took two hours. Unlike the survey on Terrain-1 which requires 3 instrument setups, it was done only by single instrument setup. From the total hours needed to complete the survey it can be seen that for Terrain-2 (total average sky view 68%), the RTK GPS survey were 1.3 times faster than the TS survey.

DTM data collection on Terrain-3 shows that the RTK GPS speed of survey significantly decreased. For this area (total average sky view 59%), the survey speed of RTK GPS is equal to TS. Both surveys required two hours to complete data collection over 209 grid-points on an area size of about 6300m^2.

With the above advantages, RTK GPS has shown a very promising prospect for generating DTM productively and efficiently. Furthermore, there is a high possibility of much better productivity and efficiency of RTK GPS when it is employed for:

i. Projects with two or three shifts (day and night)
ii. Unworkable weather for TS survey
iii. Larger working area
iv. More open area

The above possibilities are due to the pitfalls of TS survey where it can be performed only for day time work. Unlike the TS survey, RTK GPS survey can be performed either day or night since it does not require sighting and intervisibility. It can also be used during rainy weather where TS survey is unlikely can be carried out.

4.6 DTM Quality Measures

DTM quality highly depends on the accuracy of the data source or the input data. In this work, the accuracy of the RTK GPS data is assessed by comparing it to the conventional TS data. The general estimation was performed by creating profiles across the survey area (Terrain-1). The analysis was carried out by assessing the different of height value given by RTK GPS and TS data. The result is given in Table 4.4.

Table 4.4 Height of profile points.

North - South Profile				West - East Profile			
Point No.	RTK GPS (m)	TS (m)	Different (cm)	Point No.	RTK GPS (m)	TS (m)	Different (cm)
1	19.9102	19.941	3.08	1	29.0897	29.125	3.53
2	21.2585	21.292	3.35	2	27.8698	27.885	1.52
3	21.2799	21.333	5.31	3	26.9092	26.922	1.28
4	21.8983	21.928	2.97	4	26.5409	26.533	-0.79
5	22.7371	22.746	0.89	5	26.6915	26.678	-1.35
6	23.1959	23.202	0.61	6	25.5952	25.599	0.38
7	23.5779	23.575	-0.29	7	25.5009	25.503	0.21
8	23.7615	23.762	0.05	8	24.5233	24.516	-0.73
9	23.9574	23.973	1.56	9	23.6445	23.644	-0.05
10	23.8732	23.912	3.88	10	22.5459	22.555	0.91
11	23.7636	23.786	2.24	11	22.582	22.607	2.5
12	22.5432	22.555	1.18	12	20.3977	20.405	0.73
13	23.6219	23.644	2.21	13	19.0279	19.045	1.71
14	24.4735	24.516	4.25	14	18.5881	18.615	2.69
15	25.4744	25.503	2.86	15	18.744	18.772	2.8
16	25.5898	25.599	0.92	16	18.8171	18.839	2.19
17	26.6901	26.678	-1.21	17	19.4374	19.477	3.96
18	26.1628	26.149	-1.38	18	21.7293	21.752	2.27
19	25.992	25.993	0.1				
20	25.6133	25.604	-0.93				

The minimum height difference between RTK GPS and TS on the north-south profile (from 20 points) is 0.05cm, while, the maximum difference is 5.31cm. For the west-east profile (18 points), the minimum difference is 0.05cm and the maximum difference is 3.96cm. These results show that the height difference errors are small and within a common accepted threshold of 1/3 of height intervals (6.67cm). This is based on the assumption that the DTM is employed for applications of scale 1:400 where the value of the height interval is 20cm (1/3 of the interval value is 6.67). By referring to this result, the RTK GPS apparently offers a high accuracy.

However, this result is very general and can only be achieved when the sky view of the survey area is good. Hence, to have a more valid accuracy measure, in relation with the well accepted fact that RTK GPS data quality is commonly affected by the level of sky view on the surrounding of survey area, a more comprehensive height error analysis were performed on Terrain-2 and Terrain-3. Here, set of exact grid-points under various sky view were established. This was intended to have a valid estimation of how far the quality of RTK GPS data will decrease for terrain with worse sky view (Terrain-3) compared to the terrain with better sky view (Terrain-2). The comparison was carried out by comparing the height value of the grid-points given by RTK GPS to the value given by TS (complete data can be seen in Appendices D and E). Volume comparison was also used as the global parameter of the DTM quality. Absolute mean error (E_{ma}) is used as the statistical indicator of the grid-points height error. The fact that it is expressed in absolute term has the advantage that errors with different signs cannot cancel each other. Hence, it allows a more rigorous characterization of the errors. The summary of the statistical properties of the RTK GPS grid-points of Terrain-2 is given in Table 4.5.

Table 4.5 Statistical properties of Terrain-2 DTM.

Statistic	Height Error
Absolute Mean Error	2.44cm
Minimum Error	0.3cm
Maximum Error	6cm
Range	5.7cm
Error :	Amount of Points and Percentage to Total Points:
0 - 0.99cm	4 points (1.87%)
1 - 1.99cm	64 points (29.91%)
2 - 2.99cm	97 points (45.33%)
3 - 3.99cm	27 points (12.62%)
4 - 4.99cm	16 points (7.48%)
5 - 5.99cm	5 points (2.34%)
6 - 6.99cm	1 points (0.47%)
>7cm	0 points (0%)

Statistics on Table 4.5 were calculated by comparing a total of 214 grid-points. The absolute mean error of the grid-points is 2.44cm and the range of the error is 5.7cm. Overall grid-points are within the threshold (below 6.67cm). Figure 4.19 presents the plot of height errors of the grid-points.

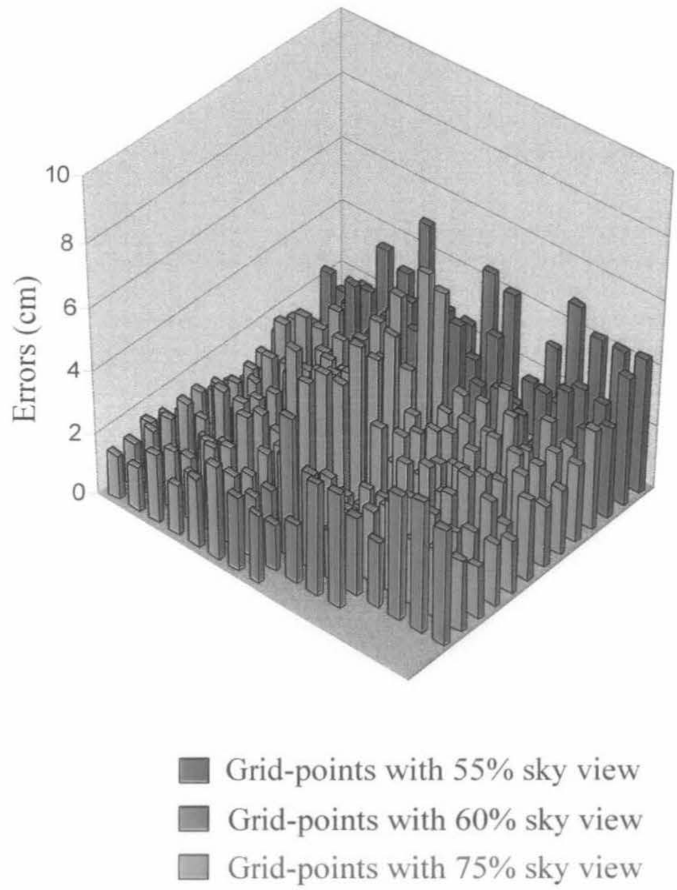


Figure 4.19 Height errors of Terrain-2 grid-points.

Referring to the plot in Figure 4.19, it can be noticed that the trend of the errors is correlated with the sky view level. The errors of the grid points with 55% and 60% sky view are relatively higher than the errors of the grid-points with 75% sky view. Yet, there is a series of grid-points (with 75% sky view) having severe error, and somehow nearly similar to the trend of grid-points with 55% or 60% sky view. This was due to the low DOP value (5) during the respective grid-points occupation, while the other grid-points were collected under DOP of 3-4.

The computed volume of the Terrain-2 DTM was 6145.245m^3, while the reference DTM was 6175.188m^3. It means that the difference of the volume is 29.943m^3. This also means that the loss volume is only 0.48% with respect to the volume of the reference DTM. It shows that Terrain-2 DTM, which was generated from RTK GPS data over area with total average sky view of 68%, is of good quality.

The DTM of Terrain-3 which has total average sky clearness 58% is comparatively lower in term of accuracy. The height errors are significantly higher compared to Terrain-2 DTM. The absolute mean error of the DTM which were calculated from 209 grid-points is 4.12cm while the range of the error is 16.685. Summary of the statistical properties of Terrain-3 DTM is given in Table 4.6.

Table 4.6 Statistical properties of Terrain-3 DTM.

Statistic	Height Error
Absolute Mean Error	4.12cm
Minimum Error	0.005cm
Maximum Error	16.69cm
Range	16.685cm
Error:	Amount of Points and Percentage to Total Points:
0 - 0.99cm	3 points (1.44%)
1 - 1.99cm	9 points (4.31%)
2 - 2.99cm	30 points (14.35%)
3 - 3.99cm	84 points (40.19%)
4 - 4.99cm	54 points (25.84%)
5 - 5.99cm	5 points (2.39%)
6 - 6.99cm	2 points (0.96%)
7 - 7.99cm	2 points (0.96%)
8 - 8.99cm	8 points (3.83%)
9 - 9.99cm	5 points (2.39%)
>10cm	7 points (3.35%)

Referring to Table 4.6 it can be seen that some of the errors exceed the threshold. Figure 4.20 shows the plot of the Terrain-3 height errors. Referring to the aforementioned plots, it is obvious that all of the large errors that exceed the threshold were contributed by grid-points with average sky view of 49%. The height errors of the respective grid-points are severely higher than the rest of the grid-points.

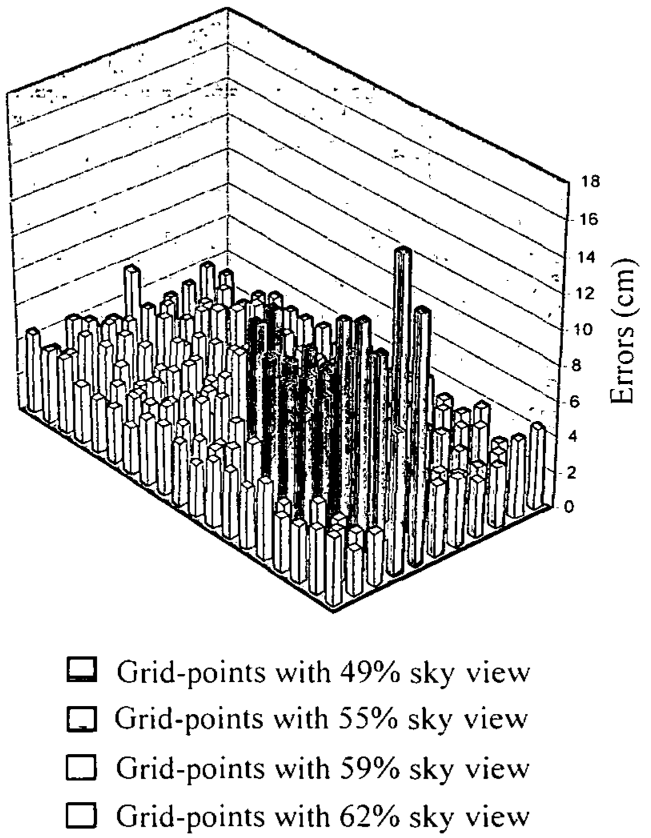


Figure 4.20 Height errors of Terrain-3 grid-points.

The errors of the grid-points (with 49% sky view) also lead to a higher volumetric error where the volume difference between Terrain-3 DTM and the reference DTM reaches 5.9% (Terrain-3 DTM volume = 2544.227m^3, reference DTM = 2693.458m^3, difference = 149.231m^3). This was proven by experimentally excluding the grid-points on the respective area, and re-computing the volume. As shown in Table 4.7, the volume difference is significantly decreased and reached 1.02%.

Table 4.7 Volume comparison of Terrain-3 DTM.

Number of Grid-point	DTM Volume			Note
	GPS	TS	Difference	
209 points	2544.227m^3	2693.458m^3	149.231m^3 (5.9%)	All grid-points used
187 points	1054.600m^3	1043.851m^3	10.749m^3 (1.02%)	22 grid-points excluded

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The method presented in this work is based on the experiment of comparing RTK GPS with the conventional TS as a means of DTM data collection. Assessments were carried out by using the measurement and DTM generated from TS as the reference of the comparison.

Result of the experiment shows that RTK GPS provides sufficient accuracy for high-resolution DTM data collection tool. It has been proven that the RTK GPS can provide centimeter level of accuracy for sky view above 50%. All existing structural features on the study area have been successfully reconstructed and represented on the DTM. Curvy terrain surfaces have not been optimally visualized since higher sampling density is required.

In comparison to classical method of TS survey, it is proven to be more productive and capable of yielding a lot of more data. Based on the experiment, for an area of 62500m^2, RTK GPS managed to collect 2269 data; those collected by TS were 1701, for the duration of approximately 16 hours. Hence RTK GPS could collect 568 more data, or 1.4 faster than conventional method. It is very productive to be employed on area with average sky view of 60% or above where the speed of survey can be maintained at about 1.4 faster than TS. Meanwhile, for average sky view between 50% and 60% it shows less productivity where the speed of survey of both techniques nearly the same. The speed of survey becomes much slower for area with average sky view of lower than 50%. RTK GPS only employed one surveyor for the job, while those employed by conventional method were two. Therefore, basically the saving cost for the man power is almost 50%. This offers a good efficiency on reducing personnel expenditure.

The application of RTK GPS for data collection tool on area with average sky view above 55% can produce a good quality of DTM, with height errors ranging from 0.3cm-6cm. The absolute mean error of the respective DTM is 2.44cm, and the volumetric error is approximately 0.5%. Lower quality of DTM was generated for area with average sky view below 55%. For this, the height errors, as well as the absolute mean error, are in centimeter level while volumetric error is about 1%. Applying RTK GPS for data collection tool on area with sky view less than 50% is not recommended since the resulting DTM might be unreliable. The experimental result showed that it reached decimeter level (16.685cm) of height error, and almost 6% of volumetric error.

5.2 Recommendations and Future Works

Further studies of applying RTK for larger survey area needs to be investigated. It will be an interesting work, since the RTK GPS might offer higher productivity. Yet, it needs to be highlighted that applying this method for larger working area requires study on the issue of geoid undulation, pertaining to the consistency of the height measurement and height references.

Visualization of the generated high resolution DTM can be optimized. This could be performed by the so called hybrid modeling, combining TIN and grid-based approach. The combination of TIN's flexibility to reconstruct abrupt and sudden changes on terrain and the ease of producing continuous surface by grid-based approach may possibly enhance the visualization of high resolution DTM.

The application of RTK GPS for DTM collection tool on terrain with sky view above 60% is recommended, since it has been proven to be more productive and efficient when employed on the respective terrain.

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APPENDICES

Appendix A

RTK GPS Equipment Specification (Topcon Hiper)

[illegible]	40 channel GPS receiver/antenna with MINTER interface
[illegible] Specification	
Tracking Channels, standard	40 L1 GPS (20 GPS L1+L2 on Cinderella[2] days)
Tracking Channels, optional	20 GPS L1+L2
Signals Tracked	L1 + L2 Carrier, C/A
Measurement Mode	Static/Rapid Static Kinematic (Continuous mode and Stop & Go mode)
[illegible]	
Static, Rapid Static	H: 3mm + 0.5ppm V: 5mm + 0.5ppm
RTK	H: 10mm + 1ppm V: 15mm + 1ppm
[illegible]	
Dimensions	
Size	W:159 x D:172 x H:88(mm)
Weight	1.65kg
Enclosure	Aluminum
Antenna	Internal, Micro-strip, Zero center, Flat ground plane
[illegible]	
Power Supply	Internal, optional external
Internal Battery	2 Li-ion, 3000 mAh , 7.4V
External Power Input	6 to 28 volts DC
Power Consumption	Less than 3.0 watts
[illegible]	
Operating Temperature	-30C° ~ +55C°
Enclosure	Aluminum extrusion, waterproof
[illegible]	
Standard Ports	2 Serial Ports (RS232)
Status Indicator	2x3-color LED's, (Green, Red, Yellow)
Interface	MINTER (FN,PWR), RESET button
[illegible]	
Memory	Up to 128 MB
Logging Intervals	Up to 20 times per second

Appendix B

TS Equipment Specification (Topcon GTS-229)

Model Name	GTS-223	GTS-225	GTS-226	GTS-229
TELESCOPE				
Length	150mm			
Objective Lens Diameter	45mm (EDM 50mm)			
Magnification	30 ×			
Image	Erect			
Field of View	1°30′			
Resolving Power	2.5″			
Minimum Focus Distance	1.3m			
DISTANCE MEASUREMENT				
Condition 1 1 prism 3 prisms 9 prisms	3,000m (9,900ft) 4,000m (13,200ft) 5,000m (16,400ft)			2,000m (6,600ft) 2,700m (8,900ft) 3,400m (11,200ft)
Condition 1: Sight haze with visibility about 20 km (12.5 miles) moderate sunlight with light heat shimmer. Condition 2: No haze with visibility about 40 km (25 miles), overcast with no heat shimmer.				
Accuracy	±(2mm + 2ppm× D)m.s.e.			±(3mm + 3ppm× D)m.s.e.
	D: Measuring distance (mm)			
Least Count in Measurement				
Fine Mode	1mm (0.005 ft.)/0.2mm (0.001 ft.)			
Coarse Mode	10mm (0.02 ft.)/1mm (0.005 ft.)			
Tracking Mode	10mm (0.02 ft.)			
Measurement Display	11 digits: max. display 9999999.9999			
Measuring Time				
Fine Mode Coarse Mode Tracking Mode	1mm: 1.2sec. (Initial 4 sec.) 0.2mm: 2.8sec. (Initial 5 sec.) 0.7sec. (Initial 3 sec.) 0.4sec. (Initial 3 sec.) (The initial time will be different by a condition and setting EDH off time.)			
Atmospheric Correction Range	-999.9 to +999.9ppm (By 0.1ppm)			
Prism Constant Correction Range	-99.9 to +99.9mm (By 0.1mm)			

Appendix C

Part of Terrain 1 Data

Point Number	Northing	Easting	Height	Code
6781	484878.570	718717.904	26.553	TOPO
6782	484875.444	718717.232	26.267	TOPO
6783	484874.663	718720.395	25.807	TOPO
6784	484876.052	718720.644	26.386	TOPO
6785	484877.925	718721.075	26.611	TOPO
6786	484880.400	718721.461	25.783	TOPO
6787	484879.618	718725.538	25.692	TOPO
6788	484877.767	718725.494	26.088	TOPO
6789	484875.857	718725.427	26.040	TOPO
6790	484874.726	718725.358	25.385	TOPO
6791	484874.752	718727.622	25.178	TOPO
6792	484876.234	718727.729	25.799	TOPO
6793	484878.054	718728.021	25.876	TOPO
6794	484879.071	718728.294	25.676	TOPO
6795	484878.414	718731.916	25.388	TOPO
6796	484876.584	718731.747	25.476	TOPO
6797	484874.820	718731.652	24.863	TOPO
6798	484874.738	718734.757	24.703	TOPO
6799	484876.292	718734.984	25.369	TOPO
6800	484877.782	718735.195	25.463	TOPO
6801	484877.352	718737.532	25.494	TOPO
6802	484877.054	718738.930	25.443	TOPO
6803	484876.024	718739.070	24.975	TOPO
6804	484875.751	718737.157	25.049	TOPO
6805	484874.753	718736.262	24.571	TOPO
6806	484874.790	718738.698	24.341	TOPO
6807	484874.744	718741.703	24.129	TOPO
6808	484876.838	718741.670	25.032	TOPO
6809	484876.747	718745.314	24.719	TOPO
6810	484874.817	718745.361	23.818	TOPO
6811	484874.752	718747.731	23.640	TOPO
6812	484876.674	718747.862	24.495	TOPO
6813	484874.755	718751.093	23.347	TOPO
6814	484874.780	718754.474	23.105	TOPO
6815	484875.349	718758.210	22.443	TOPO
6816	484875.292	718758.141	23.350	TOPO
6817	484876.351	718758.130	23.905	TOPO
6818	484876.294	718760.417	23.798	TOPO
6819	484874.909	718760.271	22.997	TOPO
6820	484874.799	718763.315	22.991	TOPO
6821	484876.266	718763.212	23.651	TOPO
6822	484876.147	718765.568	23.628	TOPO
6823	484874.982	718765.630	23.008	TOPO

Part of Terrain 1 Data (continued)

Point Number	Northing	Easting	Height	Code
6824	484874.799	718762.973	23.001	TOPO
6825	484874.818	718769.053	22.948	TOPO
6826	484876.025	718769.082	23.554	TOPO
6827	484875.960	718771.406	23.480	TOPO
6828	484874.894	718771.381	22.967	TOPO
6829	484874.861	718775.303	22.946	TOPO
6830	484874.890	718776.485	22.958	TOPO
6831	484875.734	718776.395	23.290	TOPO
6832	484875.874	718774.470	23.295	TOPO
6833	484875.590	718781.191	22.883	TOPO
6834	484871.162	718781.354	22.555	TOPO
3109	484876.635	718786.681	22.753	DRAN
3110	484875.732	718786.605	23.095	DRAN
3111	484875.814	718783.205	23.301	DRAN
3112	484876.715	718783.236	22.945	DRAN
3113	484875.911	718780.203	23.491	DRAN
3114	484876.842	718780.230	23.157	DRAN
3115	484876.914	718776.478	23.342	DRAN
3116	484875.976	718776.513	23.697	DRAN
3117	484876.045	718774.155	23.856	DRAN
3118	484876.994	718774.078	23.471	DRAN
3119	484877.111	718770.024	23.720	DRAN
3120	484876.192	718769.997	24.082	DRAN
3121	484876.218	718768.089	24.196	DRAN
3122	484877.173	718768.074	23.883	DRAN
3123	484877.292	718764.314	24.216	DRAN
3124	484876.366	718764.337	24.417	DRAN
3125	484876.536	718759.039	24.758	DRAN
3126	484877.459	718759.054	24.638	DRAN
3127	484876.691	718753.716	25.117	DRAN
3128	484877.585	718753.767	25.053	DRAN
3129	484876.829	718748.448	25.309	DRAN
3130	484877.656	718748.489	25.305	DRAN
3131	484876.915	718744.945	25.398	DRAN
3132	484877.777	718744.940	25.403	DRAN
3133	484876.994	718741.316	25.492	DRAN
3134	484877.803	718741.409	25.497	DRAN
3135	484878.037	718739.440	25.570	DRAN
3136	484877.177	718739.151	25.564	DRAN
3137	484878.260	718733.358	25.640	DRAN
3138	484879.145	718733.556	25.626	DRAN
3139	484880.072	718728.901	25.706	DRAN
3140	484879.144	718728.815	25.717	DRAN
3141	484879.969	718724.387	25.780	DRAN
3142	484880.870	718724.564	25.768	DRAN

Part of Terrain 1 Data (continued)

Point Number	Northing	Easting	Height	Code
1096	484874.535	718719.062	25.866	BRKL
1097	484874.551	718733.341	24.551	BRKL
1098	484874.734	718733.298	24.823	BRKL
1099	484874.577	718754.135	22.976	BRKL
1100	484874.747	718754.113	23.142	BRKL
1101	484874.667	718780.582	22.731	BRKL
1102	484874.822	718780.640	22.956	BRKL
5045	484873.033	718780.354	22.662	ROAD
5046	484872.985	718774.451	22.687	ROAD
5047	484872.920	718766.613	22.799	ROAD
5048	484871.488	718716.939	26.030	ROAD
5049	484873.498	718717.167	26.052	ROAD
5050	484869.743	718716.715	26.008	ROAD
5051	484869.430	718723.695	25.290	ROAD
5052	484871.138	718723.682	25.357	ROAD
5053	484873.174	718723.878	25.339	ROAD
5054	484873.037	718730.266	24.792	ROAD
5055	484871.029	718730.270	24.750	ROAD
5056	484868.597	718730.097	24.612	ROAD
5057	484868.448	718735.590	24.241	ROAD
5058	484871.107	718735.624	24.327	ROAD
5059	484873.212	718735.784	24.369	ROAD
5060	484873.252	718740.690	23.918	ROAD
5061	484870.647	718740.781	23.870	ROAD
5062	484868.822	718740.693	23.820	ROAD
5063	484868.718	718745.813	23.371	ROAD
5064	484871.407	718745.958	23.460	ROAD
5065	484873.636	718745.990	23.510	ROAD
5066	484873.585	718751.175	23.126	ROAD
5067	484871.871	718751.237	23.116	ROAD
5068	484869.934	718751.143	23.084	ROAD
5069	484870.533	718754.385	22.902	ROAD
5070	484872.921	718754.487	22.888	ROAD
5071	484874.227	718754.514	22.881	ROAD
5072	484874.345	718758.935	22.819	ROAD
5073	484872.623	718758.992	22.853	ROAD
5074	484872.685	718764.056	22.794	ROAD
5075	484868.095	718747.370	23.231	ROAD
5076	484868.167	718744.821	23.376	ROAD
5077	484868.149	718750.390	23.079	ROAD
5078	484861.386	718750.019	22.661	ROAD
5079	484861.485	718747.500	22.705	ROAD
5080	484861.787	718744.811	22.714	ROAD
5081	484857.318	718744.407	22.587	ROAD
5082	484854.927	718744.406	22.599	ROAD

Appendix D

Data of Terrain 2

Point Number	Total Station			RTK GPS			Height Error (cm)
	Northing	Easting	Height	Northing	Easting	Height	
1	484881.726	718726.63	26.092	484881.726	718726.619	26.078	1.4
2	484884.045	718727.187	26.274	484884.026	718727.193	26.288	1.4
3	484886.46	718727.781	26.358	484886.453	718727.764	26.341	1.7
4	484888.878	718728.418	26.446	484888.863	718728.426	26.431	1.5
5	484891.293	718729.095	26.482	484891.282	718729.1	26.47	1.2
6	484893.708	718729.67	26.451	484893.696	718729.65	26.436	1.5
7	484896.1	718730.368	26.383	484896.088	718730.351	26.372	1.1
8	484898.499	718731.078	26.426	484898.481	718731.086	26.436	1.0
9	484900.922	718731.628	26.667	484900.923	718731.623	26.66	0.7
10	484903.324	718732.258	26.907	484903.309	718732.259	26.895	1.2
11	484905.749	718732.921	26.973	484905.749	718732.904	26.958	1.5
12	484908.131	718733.649	27.075	484908.138	718733.635	27.059	1.6
13	484910.536	718734.257	27.135	484910.523	718734.237	27.146	1.1
14	484913.005	718734.785	27.205	484912.991	718734.766	27.181	2.4
15	484915.434	718735.405	27.341	484915.416	718735.392	27.355	1.4
16	484914.647	718740.283	26.133	484914.631	718740.268	26.152	1.9
17	484912.218	718739.737	26.113	484912.22	718739.721	26.096	1.7
18	484909.793	718739.01	26.177	484909.784	718738.99	26.167	1.0
19	484907.373	718738.439	26.161	484907.378	718738.452	26.147	1.4
20	484904.969	718737.76	26.076	484904.978	718737.741	26.065	1.1
21	484902.577	718737.104	25.885	484902.577	718737.086	25.859	2.6
22	484900.159	718736.504	25.865	484900.164	718736.491	25.851	1.4
23	484897.808	718735.827	25.919	484897.791	718735.808	25.9	1.9
24	484895.362	718735.194	25.879	484895.363	718735.176	25.861	1.8
25	484892.912	718734.615	25.802	484892.911	718734.599	25.781	2.1
26	484890.437	718733.987	25.705	484890.431	718733.998	25.691	1.4
27	484888.128	718733.316	25.66	484888.133	718733.301	25.637	2.3
28	484885.704	718732.658	25.663	484885.694	718732.644	25.641	2.2
29	484883.248	718732.029	25.682	484883.262	718732.014	25.66	2.2
30	484880.964	718731.449	25.562	484880.98	718731.437	25.548	1.4
31	484880.292	718736.302	25.679	484880.294	718736.292	25.657	2.2
32	484882.607	718736.905	25.658	484882.607	718736.895	25.639	1.9
33	484885.012	718737.571	25.726	484885.008	718737.563	25.713	1.3
34	484887.435	718738.226	25.755	484887.435	718738.212	25.74	1.5
35	484889.834	718738.877	25.824	484889.826	718738.862	25.797	2.7
36	484892.26	718739.479	25.861	484892.26	718739.462	25.845	1.6
37	484894.692	718740.086	25.875	484894.696	718740.079	25.853	2.2
38	484897.117	718740.679	25.855	484897.107	718740.69	25.881	2.6
39	484899.491	718741.41	25.824	484899.489	718741.41	25.844	2.0
40	484901.897	718742.076	25.801	484901.887	718742.069	25.833	3.2
41	484904.33	718742.662	25.97	484904.336	718742.65	25.946	2.4
42	484906.748	718743.261	25.997	484906.756	718743.242	25.971	2.6

Data of Terrain 2 (continued)

Point Number	Total Station			RTK GPS			Height Error (cm)
	Northing	Easting	Height	Northing	Easting	Height	
43	484909.136	718743.968	26.014	484909.142	718743.949	25.983	3.1
44	484911.555	718744.609	26.001	484911.557	718744.594	25.976	2.5
45	484913.989	718745.268	25.982	484913.994	718745.257	25.947	3.5
46	484913.327	718750.359	25.952	484913.314	718750.354	25.921	3.1
47	484910.902	718749.711	25.942	484910.904	718749.694	25.922	2.0
48	484908.499	718749.055	25.859	484908.492	718749.064	25.877	1.8
49	484906.061	718748.486	25.831	484906.05	718748.477	25.813	1.8
50	484903.677	718747.749	25.781	484903.69	718747.739	25.757	2.4
51	484901.279	718747.038	25.833	484901.276	718747.023	25.809	2.4
52	484898.885	718746.333	25.856	484898.892	718746.324	25.834	2.2
53	484896.458	718745.706	25.829	484896.462	718745.707	25.805	2.4
54	484894.072	718745.032	25.79	484894.061	718745.026	25.768	2.2
55	484891.641	718744.42	25.829	484891.638	718744.406	25.805	2.4
56	484889.232	718743.766	25.803	484889.238	718743.756	25.776	2.7
57	484886.827	718743.113	25.731	484886.839	718743.1	25.714	1.7
58	484884.407	718742.406	25.688	484884.41	718742.401	25.666	2.2
59	484882.304	718741.763	25.65	484882.321	718741.751	25.635	1.5
60	484879.651	718741.175	25.627	484879.664	718741.156	25.611	1.6
61	484879.046	718746.036	25.483	484879.062	718746.027	25.461	2.2
62	484881.404	718746.637	25.505	484881.415	718746.647	25.477	2.8
63	484883.802	718747.287	25.557	484883.809	718747.274	25.533	2.4
64	484886.215	718747.976	25.689	484886.213	718747.964	25.659	3.0
65	484888.613	718748.653	25.707	484888.622	718748.635	25.68	2.7
66	484891.012	718749.329	25.744	484891.016	718749.317	25.727	1.7
67	484893.429	718749.953	25.783	484893.427	718749.943	25.743	4.0
68	484895.823	718750.664	25.816	484895.827	718750.653	25.793	2.3
69	484898.224	718751.349	25.837	484898.233	718751.336	25.808	2.9
70	484900.645	718752.007	25.791	484900.637	718751.996	25.77	2.1
71	484903.049	718752.693	25.671	484903.049	718752.687	25.643	2.8
72	484905.437	718753.363	25.717	484905.439	718753.346	25.687	3.0
73	484907.88	718754.015	25.868	484907.874	718753.992	25.839	2.9
74	484910.246	718754.662	25.915	484910.246	718754.629	25.886	2.9
75	484912.679	718755.337	25.844	484912.661	718755.314	25.894	5.0
76	484912.019	718760.396	25.983	484912	718760.353	25.957	2.6
77	484909.593	718759.806	25.881	484909.562	718759.781	25.852	2.9
78	484907.189	718759.138	25.814	484907.177	718759.114	25.787	2.7
79	484904.776	718758.398	25.725	484904.767	718758.385	25.683	4.2
80	484902.415	718757.725	25.772	484902.404	718757.709	25.747	2.5
81	484899.977	718756.998	25.8	484899.982	718756.997	25.781	1.9
82	484897.605	718756.295	25.784	484897.597	718756.289	25.756	2.8
83	484895.21	718755.587	25.743	484895.209	718755.581	25.711	3.2
84	484892.791	718754.954	25.752	484892.791	718754.958	25.736	1.6
85	484890.373	718754.249	25.679	484890.379	718754.231	25.665	1.4
86	484887.979	718753.567	25.556	484887.976	718753.563	25.536	2.0

Data of Terrain 2 (continued)

Point Number	Total Station			RTK GPS			Height Error (cm)
	Northing	Easting	Height	Northing	Easting	Height	
87	484885.574	718752.907	25.417	484885.569	718752.902	25.395	2.2
88	484883.146	718752.156	25.472	484883.155	718752.145	25.453	1.9
89	484880.757	718751.577	25.365	484880.776	718751.555	25.342	2.3
90	484878.449	718750.921	25.336	484878.472	718750.903	25.306	3.0
91	484877.909	718755.766	25.038	484877.939	718755.737	25.014	2.4
92	484880.232	718756.431	25.059	484880.234	718756.416	25.039	2.0
93	484882.618	718757.135	25.062	484882.626	718757.119	25.044	1.8
94	484885.034	718757.813	25.14	484885.032	718757.792	25.115	2.5
95	484887.429	718758.54	25.294	484887.43	718758.522	25.262	3.2
96	484889.816	718759.223	25.501	484889.822	718759.194	25.457	4.4
97	484892.222	718759.903	25.595	484892.207	718759.908	25.577	1.8
98	484894.619	718760.607	25.609	484894.613	718760.592	25.592	1.7
99	484897.041	718761.248	25.669	484897.03	718761.22	25.636	3.3
100	484899.434	718761.919	25.749	484899.43	718761.906	25.742	0.7
101	484901.839	718762.62	25.734	484901.82	718762.603	25.717	1.7
102	484904.238	718763.349	25.711	484904.224	718763.331	25.697	1.4
103	484906.63	718764.045	25.729	484906.624	718764.028	25.712	1.7
104	484909.065	718764.698	25.828	484909.049	718764.678	25.816	1.2
105	484911.434	718765.362	25.815	484911.429	718765.334	25.79	2.5
106	484910.934	718770.325	25.745	484910.933	718770.283	25.7	4.5
107	484908.541	718769.678	25.701	484908.53	718769.645	25.68	2.1
108	484906.13	718768.973	25.584	484906.147	718768.913	25.548	3.6
109	484903.735	718768.253	25.565	484903.739	718768.242	25.515	5.0
110	484901.336	718767.48	25.561	484901.336	718767.51	25.621	6.0
111	484898.946	718766.817	25.625	484898.948	718766.796	25.592	3.3
112	484896.533	718766.118	25.573	484896.553	718766.091	25.525	4.8
113	484894.136	718765.395	25.504	484894.153	718765.369	25.46	4.4
114	484891.725	718764.734	25.349	484891.744	718764.71	25.297	5.2
115	484889.317	718764.051	25.235	484889.349	718764.044	25.191	4.4
116	484886.943	718763.368	24.99	484886.949	718763.359	24.939	5.1
117	484884.541	718762.622	24.854	484884.547	718762.605	24.802	5.2
118	484882.152	718761.902	24.72	484882.153	718761.894	24.675	4.5
119	484879.701	718761.236	24.659	484879.721	718761.229	24.644	1.5
120	484877.493	718760.649	24.614	484877.516	718760.594	24.592	2.2
121	484879.258	718766.167	24.346	484879.266	718766.114	24.327	1.9
122	484881.598	718766.764	24.433	484881.61	718766.723	24.402	3.1
123	484883.963	718767.461	24.535	484883.968	718767.434	24.509	2.6
124	484886.366	718768.166	24.645	484886.373	718768.146	24.629	1.6
125	484888.641	718768.865	24.81	484888.652	718768.848	24.802	0.8
126	484891.145	718769.617	24.968	484891.155	718769.6	24.938	3.0
127	484893.544	718770.308	25.051	484893.532	718770.297	25.037	1.4
128	484895.94	718771.029	25.152	484895.924	718771.046	25.126	2.6
129	484898.342	718771.735	25.233	484898.353	718771.746	25.218	1.5
130	484900.733	718772.429	25.3	484900.754	718772.413	25.281	1.9

Data of Terrain 2 (continued)

Point Number	Total Station			RTK GPS			Height Error (cm)
	Northing	Easting	Height	Northing	Easting	Height	
131	484903.133	718773.122	25.367	484903.147	718773.099	25.346	2.1
132	484905.499	718773.864	25.417	484905.509	718773.846	25.397	2.0
133	484907.888	718774.569	25.6	484907.892	718774.537	25.568	3.2
134	484910.327	718775.255	25.765	484910.326	718775.215	25.723	4.2
135	484909.584	718780.166	25.546	484909.592	718780.121	25.563	1.7
136	484907.186	718779.448	25.362	484907.206	718779.424	25.348	1.4
137	484904.808	718778.731	25.236	484904.831	718778.741	25.214	2.2
138	484902.42	718778.006	25.151	484902.438	718777.999	25.129	2.2
139	484900.014	718777.347	25.025	484900.031	718777.321	25.005	2.0
140	484897.63	718776.61	24.938	484897.646	718776.594	24.918	2.0
141	484895.253	718775.913	24.886	484895.264	718775.892	24.861	2.5
142	484892.858	718775.202	24.688	484892.871	718775.186	24.66	2.8
143	484890.472	718774.47	24.546	484890.479	718774.48	24.515	3.1
144	484888.09	718773.741	24.368	484888.11	718773.751	24.353	1.5
145	484885.69	718773.018	24.247	484885.714	718773.018	24.225	2.2
146	484883.303	718772.299	24.156	484883.327	718772.294	24.137	1.9
147	484881.027	718771.608	24.11	484881.039	718771.604	24.094	1.6
148	484878.683	718770.977	24.042	484878.702	718770.945	24.006	3.6
149	484878.116	718775.882	23.68	484878.129	718775.847	23.643	3.7
150	484880.453	718776.481	23.856	484880.472	718776.463	23.831	2.5
151	484882.761	718777.179	23.887	484882.763	718777.157	23.864	2.3
152	484885.152	718777.831	23.9	484885.179	718777.842	23.88	2.0
153	484887.522	718778.604	24.099	484887.545	718778.591	24.069	3.0
154	484889.904	718779.382	24.29	484889.921	718779.372	24.268	2.2
155	484892.292	718780.102	24.396	484892.316	718780.1	24.374	2.2
156	484894.685	718780.81	24.46	484894.708	718780.826	24.443	1.7
157	484897.077	718781.541	24.58	484897.092	718781.528	24.562	1.8
158	484899.466	718782.267	24.768	484899.472	718782.246	24.748	2.0
159	484901.858	718782.99	24.89	484901.871	718782.968	24.86	3.0
160	484904.263	718783.7	24.972	484904.264	718783.686	24.954	1.8
161	484906.65	718784.422	25.064	484906.643	718784.425	25.067	0.3
162	484909.042	718785.112	25.234	484909.049	718785.084	25.202	3.2
163	484908.428	718790.052	24.929	484908.434	718790.01	24.88	4.9
164	484905.96	718789.327	24.758	484905.989	718789.312	24.737	2.1
165	484903.604	718788.578	24.729	484903.621	718788.573	24.7	2.9
166	484901.226	718787.84	24.622	484901.24	718787.852	24.608	1.4
167	484898.803	718787.129	24.448	484898.824	718787.111	24.419	2.9
168	484896.472	718786.319	24.313	484896.492	718786.309	24.287	2.6
169	484894.089	718785.586	24.146	484894.102	718785.594	24.131	1.5
170	484891.652	718784.893	23.995	484891.669	718784.885	23.971	2.4
171	484889.303	718784.196	23.861	484889.318	718784.189	23.841	2.0
172	484886.914	718783.442	23.68	484886.948	718783.427	23.647	3.3
173	484884.556	718782.67	23.526	484884.58	718782.677	23.499	2.7
174	484882.159	718781.936	23.548	484882.189	718781.924	23.519	2.9

Data of Terrain 2 (continued)

Point Number	Total Station			RTK GPS			Height Error (cm)
	Northing	Easting	Height	Northing	Easting	Height	
175	484879.865	718781.259	23.473	484879.891	718781.226	23.494	2.1
176	484879.256	718786.097	23.121	484879.281	718786.048	23.081	4.0
177	484881.527	718786.863	22.976	484881.514	718786.842	22.955	2.1
178	484883.861	718787.574	23.141	484883.848	718787.559	23.115	2.6
179	484886.234	718788.32	23.316	484886.216	718788.294	23.288	2.8
180	484888.619	718788.982	23.432	484888.589	718788.976	23.402	3.0
181	484890.961	718789.859	23.592	484890.94	718789.852	23.566	2.6
182	484893.344	718790.562	23.796	484893.373	718790.549	23.776	2.0
183	484895.69	718791.317	24.035	484895.718	718791.308	24.01	2.5
184	484898.133	718791.997	24.086	484898.133	718791.998	24.076	1.0
185	484900.471	718792.765	24.249	484900.491	718792.747	24.222	2.7
186	484902.875	718793.512	24.405	484902.901	718793.493	24.372	3.3
187	484905.256	718794.274	24.492	484905.272	718794.251	24.462	3.0
188	484907.642	718795.06	24.581	484907.676	718795.019	24.539	4.2
189	484907.137	718800.035	24.072	484907.156	718799.999	24.03	4.2
190	484904.728	718799.338	24.018	484904.72	718799.313	23.989	2.9
191	484902.322	718798.57	23.934	484902.323	718798.548	23.91	2.4
192	484899.945	718797.79	23.875	484899.942	718797.776	23.852	2.3
193	484897.564	718797.074	23.781	484897.581	718797.052	23.756	2.5
194	484895.195	718796.285	23.572	484895.189	718796.266	23.547	2.5
195	484892.857	718795.526	23.303	484892.86	718795.505	23.277	2.6
196	484890.452	718794.763	23.08	484890.447	718794.782	23.066	1.4
197	484888.056	718794.058	23.09	484888.071	718794.035	23.064	2.6
198	484885.692	718793.254	22.865	484885.699	718793.24	22.845	2.0
199	484883.317	718792.494	22.791	484883.316	718792.507	22.767	2.4
200	484880.924	718791.7	22.761	484880.929	718791.714	22.739	2.2
201	484878.702	718790.94	22.575	484878.728	718790.902	22.533	4.2
202	484877.931	718795.732	22.383	484877.964	718795.692	22.346	3.7
203	484880.218	718796.483	22.48	484880.219	718796.465	22.457	2.3
204	484882.595	718797.214	22.466	484882.598	718797.2	22.449	1.7
205	484884.949	718797.997	22.455	484884.967	718797.973	22.435	2.0
206	484887.359	718798.738	22.467	484887.36	718798.722	22.45	1.7
207	484889.726	718799.496	22.626	484889.733	718799.473	22.6	2.6
208	484892.109	718800.297	22.855	484892.105	718800.313	22.835	2.0
209	484894.664	718801.16	22.955	484894.668	718801.171	22.934	2.1
210	484896.85	718801.841	23.125	484896.841	718801.824	23.1	2.5
211	484899.218	718802.609	23.293	484899.226	718802.591	23.261	3.2
212	484901.575	718803.403	23.422	484901.589	718803.378	23.393	2.9
213	484903.956	718804.156	23.534	484903.978	718804.117	23.493	4.1
214	484906.361	718804.926	23.686	484906.386	718804.884	23.643	4.3

Appendix E

Data of Terrain 3

Point Number	Total Station			RTK GPS			Height Error (cm)
	Northing	Easting	Height	Northing	Easting	Height	
1	485064.756	718811.361	26.141	485064.771	718811.334	26.102	3.9
2	485064.746	718808.876	26.045	485064.765	718808.849	26.082	3.7
3	485064.773	718806.35	26.072	485064.783	718806.34	26.105	3.3
4	485064.794	718803.844	26.112	485064.811	718803.864	26.081	3.1
5	485064.781	718801.372	26.058	485064.797	718801.34	26.102	4.4
6	485064.826	718798.876	26.054	485064.823	718798.888	26.019	3.5
7	485064.866	718796.365	26.039	485064.878	718796.333	26.077	3.8
8	485064.917	718793.837	26.051	485064.907	718793.807	26.013	3.8
9	485064.937	718791.365	26.176	485064.936	718791.343	26.146	3.0
10	485064.986	718788.761	26.219	485064.966	718788.736	26.183	3.6
11	485065.008	718786.256	26.121	485064.998	718786.227	26.081	4.0
12	485065.066	718783.767	26.226	485065.045	718783.748	26.188	3.8
13	485065.108	718781.244	26.197	485065.092	718781.229	26.17	2.7
14	485065.188	718778.762	26.118	485065.17	718778.749	26.086	3.2
15	485065.214	718776.212	26.002	485065.195	718776.201	25.971	3.1
16	485065.128	718773.83	26.596	485065.098	718773.823	26.563	3.3
17	485065.101	718771.273	27.622	485065.066	718771.28	27.665	4.3
18	485065.161	718768.673	28.705	485065.13	718768.689	28.663	4.2
19	485065.173	718766.732	28.636	485065.136	718766.755	28.682	4.6
20	485069.934	718766.704	28.674	485069.915	718766.723	28.706	3.2
21	485069.904	718768.77	28.698	485069.881	718768.793	28.733	3.5
22	485069.958	718770.823	27.959	485069.928	718770.83	28.01	5.1
23	485069.95	718773.288	26.905	485069.935	718773.281	26.888	1.7
24	485070.084	718776.222	26.014	485070.058	718776.211	25.89	3.4
25	485070.106	718778.729	26.075	485070.077	718778.717	26.042	3.3
26	485070.085	718781.221	26.225	485070.053	718781.207	26.19	3.5
27	485070.084	718783.747	26.238	485070.054	718783.714	26.198	4.0
28	485070.072	718786.244	26.19	485070.052	718786.205	26.155	3.5
29	485070.072	718788.724	26.195	485070.046	718788.704	26.163	3.2
30	485070.074	718791.326	26.153	485070.068	718791.292	26.12	3.3
31	485070.031	718793.768	26.084	485070.019	718793.741	26.044	4.0
32	485070.03	718796.3	26.03	485070.017	718796.271	26.045	1.5
33	485069.997	718798.807	26.05	485070.002	718798.768	26.065	1.5
34	485069.917	718801.329	26.049	485069.907	718801.306	26.022	2.7
35	485069.812	718803.828	26.041	485069.781	718803.786	26.036	1.5
36	485069.762	718806.344	26.05	485069.736	718806.313	26.09	4.0
37	485069.721	718808.92	26.074	485069.714	718808.898	26.043	3.1
38	485069.753	718811.398	26.17	485069.743	718811.381	26.144	2.6
39	485074.689	718811.389	26.231	485074.674	718811.397	26.201	3.0
40	485074.646	718808.875	26.103	485074.657	718808.856	26.079	2.4
41	485074.721	718806.364	26.098	485074.701	718806.375	26.073	2.5
42	485074.71	718803.868	26.037	485074.763	718803.876	26.124	8.7

Data of Terrain 3 (continued)

Point Number	Total Station			RTK GPS			Height Error (cm)
	Northing	Easting	Height	Northing	Easting	Height	
43	485074.745	718801.31	26.042	485074.781	718801.352	26.115	7.3
44	485074.821	718798.818	26.037	485074.851	718798.787	26.12	8.3
45	485074.874	718796.277	26.049	485074.908	718796.3	26.141	9.2
46	485074.895	718793.821	26.092	485074.873	718793.794	26.129	3.7
47	485074.902	718791.298	26.181	485074.879	718791.266	26.138	4.3
48	485075.003	718789.05	26.202	485074.979	718789.047	26.178	2.4
49	485075.001	718786.327	26.138	485074.969	718786.307	26.095	4.3
50	485075.041	718783.792	26.188	485075.006	718783.786	26.228	4.0
51	485075.063	718781.281	26.227	485075.04	718781.269	26.258	3.1
52	485075.085	718778.638	26.092	485075.06	718778.618	26.055	3.7
53	485075.103	718776.231	26.025	485075.089	718776.215	26.001	2.4
54	485075.015	718773.625	26.757	485074.988	718773.623	26.791	3.4
55	485075.064	718770.733	28.007	485075.034	718770.708	28.047	4.0
56	485075.035	718768.718	28.782	485074.987	718768.714	28.831	4.9
57	485074.906	718766.802	28.7	485074.872	718766.821	28.744	4.4
58	485080.277	718766.993	28.826	485080.287	718767.016	28.791	3.5
59	485080.253	718769.433	28.491	485080.247	718769.471	28.449	4.2
60	485080.215	718771.766	27.607	485080.183	718771.759	27.566	4.1
61	485080.169	718773.726	26.747	485080.152	718773.732	26.729	1.8
62	485080.147	718776.199	26.021	485080.127	718776.197	25.997	2.4
63	485080.077	718778.758	26.048	485080.059	718778.731	26.01	3.8
64	485080.015	718781.254	26.226	485079.988	718781.221	26.199	4.7
65	485080.005	718783.746	26.241	485079.982	718783.739	26.217	2.4
66	485079.98	718786.269	26.199	485079.959	718786.244	26.159	4.0
67	485079.93	718788.765	26.154	485079.904	718788.724	26.225	7.1
68	485079.917	718791.262	26.173	485079.889	718791.217	26.267	9.4
69	485079.846	718793.756	26.094	485079.833	718793.705	25.986	10.8
70	485079.824	718796.255	26.051	485079.822	718796.206	25.967	8.4
71	485079.674	718798.761	26.051	485079.644	718798.813	26.132	8.1
72	485079.739	718801.261	26.039	485079.701	718801.297	26.129	9.0
73	485079.701	718803.769	26.025	485079.644	718803.839	26.149	12.4
74	485079.68	718806.266	26.099	485079.609	718806.329	26.228	12.9
75	485079.645	718808.765	26.175	485079.627	718808.804	26.058	11.7
76	485079.621	718811.329	26.179	485079.611	718811.295	26.098	8.1
77	485084.512	718811.442	26.201	485084.561	718811.375	26.06	14.1
78	485084.443	718808.908	26.169	485084.473	718808.839	26.002	16.7
79	485084.37	718806.236	25.282	485084.381	718806.198	25.187	9.5
80	485084.371	718803.897	26.076	485084.409	718803.868	25.972	10.4
81	485084.442	718801.203	26.059	485084.411	718801.228	25.967	9.2
82	485084.498	718798.705	26.033	485084.471	718798.741	25.951	8.2
83	485084.567	718796.213	26.062	485084.551	718796.264	25.976	8.6
84	485084.618	718793.697	26.11	485084.598	718793.656	26.048	6.2
85	485084.687	718791.206	26.183	485084.684	718791.163	26.096	8.7
86	485084.722	718788.7	26.256	485084.702	718788.668	26.213	4.3

Data of Terrain 3 (continued)

Point Number	Total Station			RTK GPS			Height Error (cm)
	Northing	Easting	Height	Northing	Easting	Height	
87	485084.799	718786.188	26.208	485084.781	718786.167	26.198	3.0
88	485084.828	718783.686	26.223	485084.799	718783.666	26.182	4.1
89	485084.898	718781.188	26.167	485084.878	718781.171	26.14	2.7
90	485084.979	718778.703	26.069	485084.967	718778.694	26.05	1.9
91	485085.072	718776.227	26.019	485085.051	718776.26	25.975	4.4
92	485085.04	718773.723	26.791	485085.021	718773.719	26.769	2.2
93	485084.952	718771.843	27.532	485084.931	718771.828	27.502	3.0
94	485085.104	718769.178	28.594	485085.076	718769.182	28.633	3.9
95	485084.922	718766.987	28.754	485084.945	718766.967	28.788	3.4
96	485089.904	718767.246	29.193	485089.867	718767.214	29.251	5.8
97	485089.989	718769.041	29.181	485089.964	718769.015	29.139	4.2
98	485089.904	718771.76	27.669	485089.874	718771.743	27.627	4.2
99	485089.989	718773.589	26.809	485089.979	718773.585	26.792	1.7
100	485090.026	718776.223	25.978	485090.002	718776.229	25.95	2.8
101	485089.947	718778.74	26.045	485089.926	718778.742	26.023	2.2
102	485089.93	718781.263	26.126	485089.911	718781.265	26.111	1.5
103	485089.849	718783.683	26.223	485089.863	718783.679	26.198	2.5
104	485089.818	718786.24	26.152	485089.796	718786.222	26.104	4.8
105	485089.786	718788.724	26.197	485089.768	718788.697	26.239	4.2
106	485089.738	718791.248	26.18	485089.718	718791.217	26.222	4.2
107	485089.721	718793.7	26.131	485089.698	718793.671	26.088	4.3
108	485089.68	718796.255	26.112	485089.643	718796.212	26.046	6.6
109	485089.657	718798.702	26.115	485089.644	718798.739	26.155	4.0
110	485089.614	718801.237	26.075	485089.596	718801.216	26.043	3.2
111	485089.6	718803.701	26.073	485089.584	718803.682	26.04	3.3
112	485089.582	718806.236	26.113	485089.609	718806.267	26.07	4.3
113	485089.533	718808.691	26.141	485089.558	718808.712	26.104	3.7
114	485089.527	718811.325	26.217	485089.499	718811.356	26.176	4.1
115	485094.49	718811.292	26.205	485094.463	718811.317	26.166	3.9
116	485094.399	718808.801	26.205	485094.38	718808.818	26.175	3.0
117	485094.476	718806.301	26.138	485094.471	718806.329	26.107	3.1
118	485094.55	718803.79	26.079	485094.535	718803.807	26.054	2.5
119	485094.629	718801.281	26.075	485094.593	718801.262	26.028	4.7
120	485094.659	718798.793	26.139	485094.641	718798.766	26.097	4.2
121	485094.7	718796.298	26.137	485094.691	718796.263	26.091	4.6
122	485094.644	718793.776	26.108	485094.616	718793.75	26.07	3.8
123	485094.678	718791.29	26.151	485094.658	718791.265	26.115	3.6
124	485094.695	718788.791	26.188	485094.669	718788.769	26.224	3.6
125	485094.731	718786.275	26.145	485094.699	718786.246	26.192	4.7
126	485094.759	718783.78	26.145	485094.737	718783.764	26.179	3.4
127	485094.84	718781.285	26.136	485094.812	718781.26	26.177	4.1
128	485094.86	718778.776	26.065	485094.848	718778.753	26.074	0.9
129	485095.009	718776.245	26.003	485094.988	718776.223	25.97	3.3
130	485095.01	718773.88	26.761	485094.982	718773.883	26.73	3.1

Data of Terrain 3 (continued)

Point Number	Total Station			RTK GPS			Height Error (cm)
	Northing	Easting	Height	Northing	Easting	Height	
131	485094.956	718771.775	27.657	485094.958	718771.794	27.637	2.0
132	485094.841	718769.156	28.742	485094.837	718769.124	28.781	3.9
133	485094.781	718767.031	28.797	485094.769	718767.016	28.786	2.1
134	485100.014	718767.129	28.61	485100.029	718767.118	28.642	3.3
135	485100.004	718769.248	28.73	485099.99	718769.228	28.77	2.5
136	485100.062	718771.743	27.538	485100.075	718771.772	27.502	3.6
137	485099.871	718773.651	26.666	485099.899	718773.675	26.624	4.2
138	485100.06	718776.296	25.99	485100.048	718776.281	25.966	2.4
139	485100.003	718778.779	26.026	485099.984	718778.739	26.021	0.5
140	485099.955	718781.282	26.031	485099.933	718781.251	26.024	0.7
141	485099.888	718783.777	26.105	485099.873	718783.748	26.079	3.6
142	485099.846	718786.271	26.091	485099.833	718786.243	26.058	3.3
143	485099.785	718788.773	26.163	485099.782	718788.74	26.201	3.8
144	485099.686	718791.266	26.071	485099.667	718791.237	26.106	3.5
145	485099.6	718793.771	26.108	485099.578	718793.737	26.149	4.1
146	485099.594	718796.282	26.075	485099.571	718796.289	26.035	4.0
147	485099.563	718798.782	26.153	485099.601	718798.768	26.197	4.4
148	485099.508	718801.277	26.114	485099.543	718801.309	26.154	5.0
149	485099.522	718803.781	26.116	485099.492	718803.806	26.074	4.2
150	485099.484	718806.284	26.124	485099.505	718806.273	26.149	2.5
151	485099.445	718808.763	26.133	485099.461	718808.785	26.163	3.0
152	485099.441	718811.285	26.192	485099.423	718811.312	26.224	3.2
153	485104.424	718811.288	26.204	485104.447	718811.308	26.239	3.5
154	485104.45	718808.774	26.135	485104.469	718808.756	26.096	2.9
155	485104.46	718806.278	26.153	485104.482	718806.255	26.121	3.2
156	485104.503	718803.755	26.17	485104.523	718803.776	26.206	3.6
157	485104.52	718801.278	26.134	485104.5	718801.302	26.167	3.3
158	485104.626	718798.778	26.109	485104.614	718798.74	26.149	4.0
159	485104.66	718796.284	26.09	485104.633	718796.314	26.14	5.0
160	485104.76	718793.783	26.146	485104.74	718793.792	26.116	3.0
161	485104.792	718791.28	26.09	485104.759	718791.304	26.05	4.0
162	485104.827	718788.776	26.1	485104.863	718788.758	26.06	4.0
163	485104.842	718786.258	26.038	485104.815	718786.268	26.001	3.7
164	485104.917	718783.781	26.021	485104.939	718783.752	25.985	3.6
165	485104.944	718781.279	26.01	485104.974	718781.294	25.97	4.0
166	485105.016	718778.78	25.99	485104.992	718778.75	25.95	4.0
167	485105.078	718776.326	26.002	485105.062	718776.309	25.976	2.6
168	485105.132	718773.906	26.682	485105.112	718773.879	26.645	3.7
169	485105.21	718771.63	27.619	485105.195	718771.61	27.587	3.2
170	485105.277	718769.299	28.628	485105.269	718769.324	28.658	3.0
171	485105.275	718766.943	28.756	485105.291	718766.966	28.791	3.5
172	485110.247	718769.294	28.751	485110.211	718769.283	28.71	4.1
173	485110.245	718766.939	28.623	485110.224	718766.963	28.59	3.3
174	485110.243	718771.704	27.742	485110.228	718771.69	27.714	2.8

Data of Terrain 3 (continued)

Point Number	Total Station			RTK GPS			Height Error (cm)
	Northing	Easting	Height	Northing	Easting	Height	
175	485110.167	718773.997	26.776	485110.145	718773.979	26.741	3.5
176	485110.061	718776.336	26.014	485110.046	718776.315	25.979	3.5
177	485110.064	718778.823	25.975	485110.044	718778.81	26.002	2.7
178	485110.068	718781.31	26.033	485110.092	718781.28	26.077	4.4
179	485110.016	718783.822	26.058	485109.996	718783.834	26.032	2.6
180	485109.949	718786.32	26.117	485109.926	718786.308	26.09	2.7
181	485109.852	718788.831	26.167	485109.871	718788.812	26.134	3.3
182	485109.816	718791.311	26.103	485109.843	718791.332	26.145	4.2
183	485109.741	718793.82	26.081	485109.752	718793.857	26.041	4.0
184	485109.712	718796.318	26.026	485109.742	718796.289	26.069	4.3
185	485109.685	718798.829	26.004	485109.659	718798.809	26.054	5.0
186	485109.634	718801.34	25.999	485109.651	718801.309	26.037	3.8
187	485109.609	718803.821	26.098	485109.595	718803.801	26.122	3.4
188	485109.539	718806.321	26.12	485109.564	718806.303	26.16	4.0
189	485109.49	718808.829	26.18	485109.473	718808.852	26.211	3.1
190	485109.403	718811.333	26.21	485109.425	718811.303	26.255	4.5
191	485114.385	718811.307	26.162	485114.35	718811.282	26.208	4.6
192	485114.488	718808.814	26.101	485114.498	718808.842	26.134	3.3
193	485114.521	718806.309	26.021	485114.545	718806.319	26.047	2.6
194	485114.529	718803.823	25.985	485114.559	718803.806	26.025	4.0
195	485114.555	718801.335	25.982	485114.537	718801.324	25.951	3.1
196	485114.61	718798.811	26.022	485114.589	718798.791	25.989	3.3
197	485114.81	718796.318	25.981	485114.83	718796.328	25.951	3.0
198	485114.643	718793.785	26.096	485114.66	718793.765	26.062	3.4
199	485114.612	718791.316	26.137	485114.588	718791.304	26.107	3.0
200	485114.674	718788.818	26.171	485114.664	718788.842	26.144	2.7
201	485114.725	718786.314	26.131	485114.71	718786.288	26.1	3.1
202	485114.784	718783.821	26.151	485114.804	718783.832	26.122	2.9
203	485114.835	718781.317	26.046	485114.802	718781.309	26.012	3.4
204	485114.914	718778.834	26.035	485114.935	718778.824	26.009	2.6
205	485114.971	718776.299	26.119	485114.951	718776.28	26.087	3.2
206	485115.19	718773.997	26.042	485115.201	718773.973	26.007	3.5
207	485115.19	718771.626	27.724	485115.171	718771.636	27.754	3.0
208	485115.191	718769.292	28.627	485115.203	718769.277	28.646	1.9
209	485115.192	718766.938	28.755	485115.169	718766.933	28.786	3.1